

WIMPZILLAS

Production and Detection
of Supermassive
Dark Matter



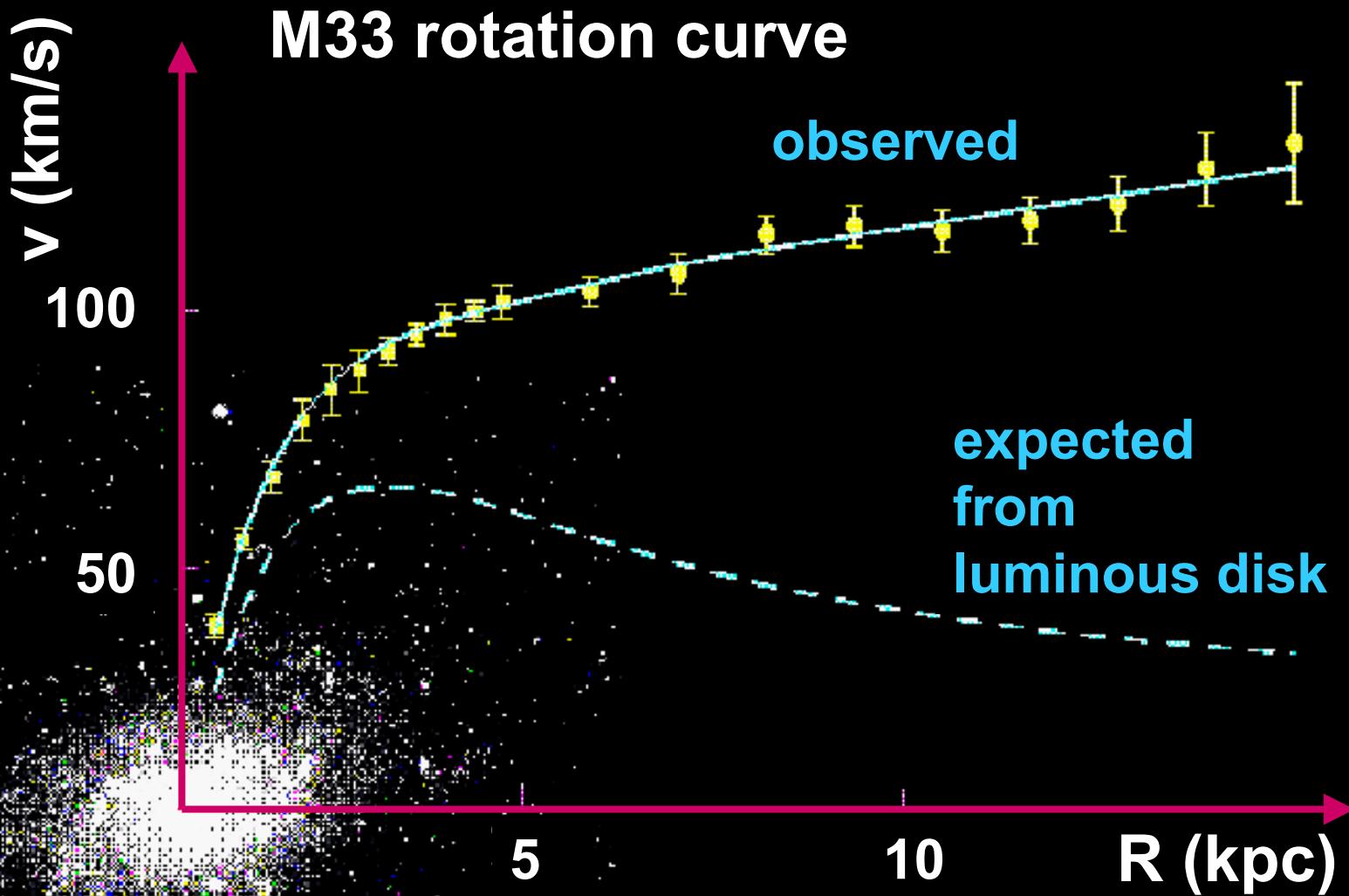
Rocky Kolb, *Fermilab/Chicago/CERN*
Collège de France, 5 April 2002

Composition of the universe?



M63

Galaxies: Building blocks of the (visible) universe



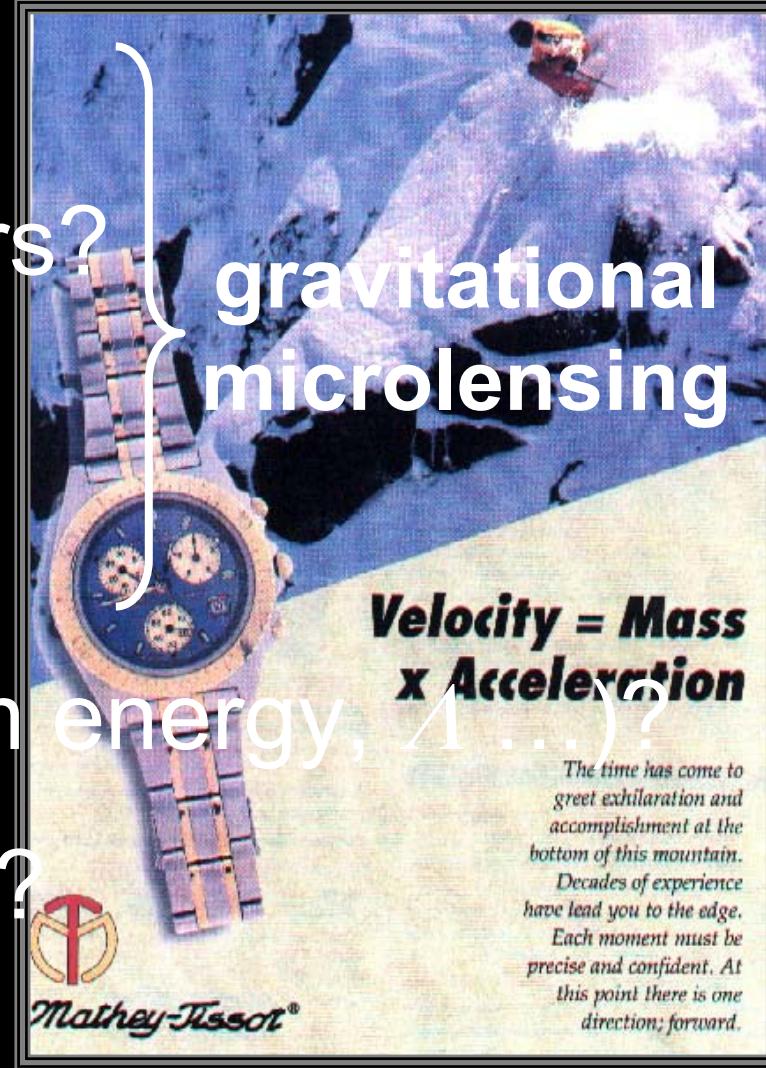
- galaxy & cluster dynamics
- gravitational lensing
- structure formation
- CMB observations

Missing pieces



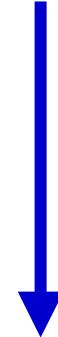
Missing pieces

- Modified Newtonian dynamics?
- Planets?
- Mass disadvantaged stars?
brown red white
- Black holes?
- Weight of space (vacuum energy, Λ ...)?
- Nonbaryonic dark matter?



Nonbaryonic dark matter

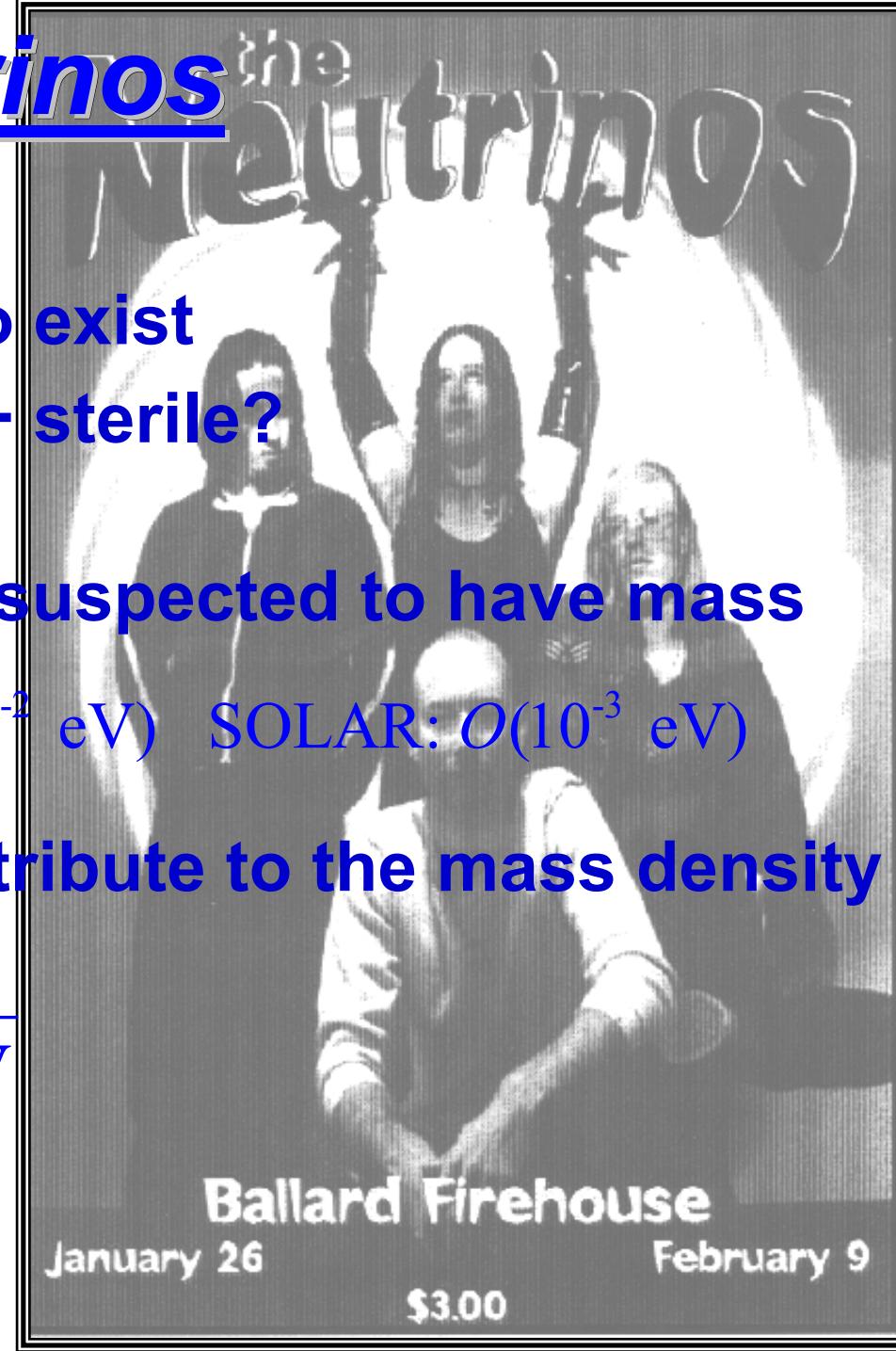
- neutrinos (hot dark matter)
- sterile neutrinos, gravitinos (warm dark matter)
- LSP (neutralino, sneutrino, ...) (cold dark matter)
- axion, axion clusters
- WIMPZILLAS
- solitons (B-balls; Q-balls; Odd-balls,....)
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 -
 -
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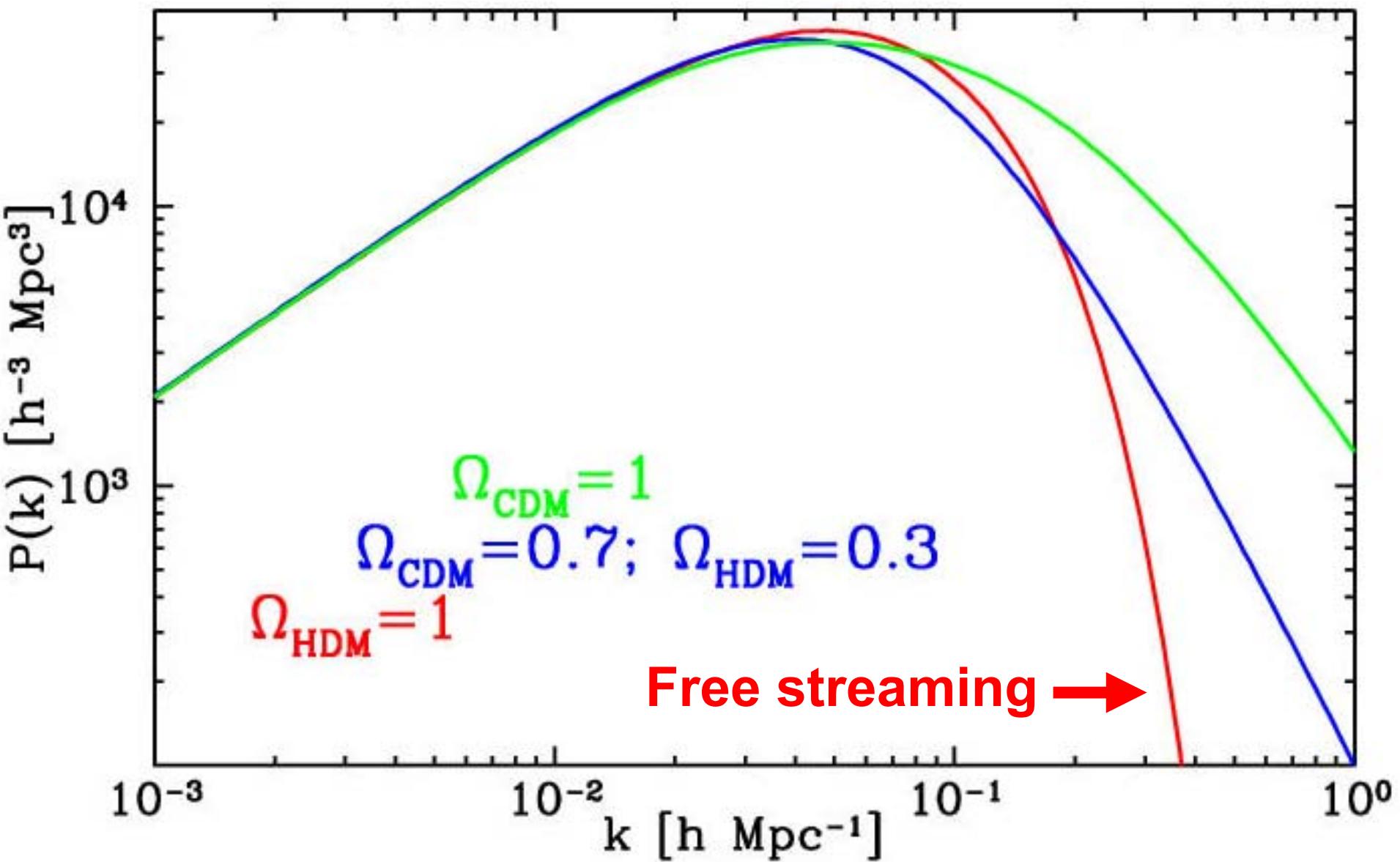
Neutrinos

- Neutrinos are known to exist
three active + sterile?
- Neutrinos are strongly suspected to have mass
LSND $O(\text{eV})$ ATM: $O(10^{-2} \text{ eV})$ SOLAR: $O(10^{-3} \text{ eV})$
- Massive neutrinos contribute to the mass density

$$\Omega_{\nu\bar{\nu}} h^2 = \frac{m_\nu}{90 \text{ eV}}$$



Free streaming

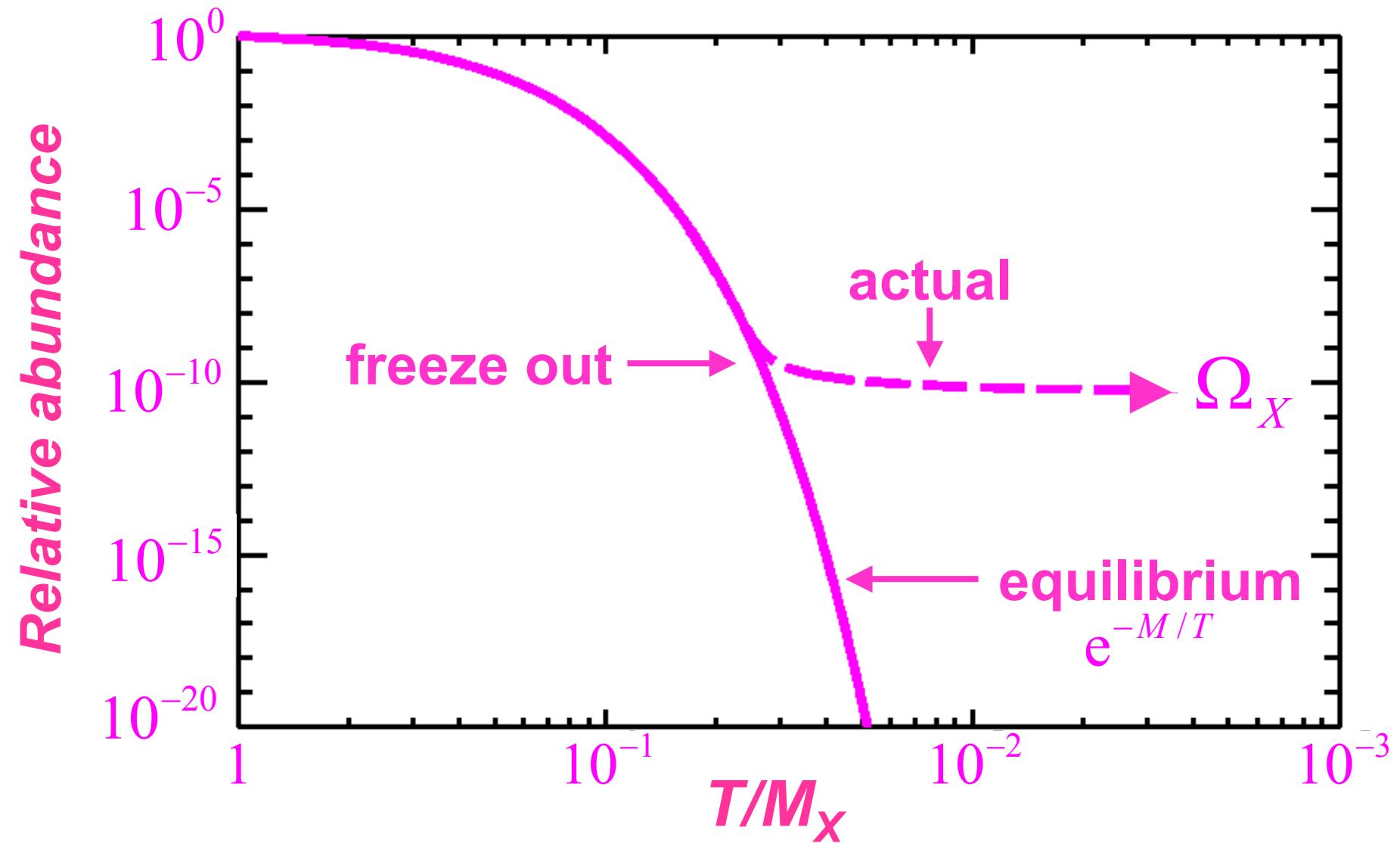


Sterile neutrinos & gravitinos

- weaker interactions
- decouple earlier
- diluted more
- can have larger mass
- smaller velocity
- “warm”
- help solve satellite & cusp problem?

Particle models with sterile neutrinos or gravitinos in desired mass range are “unfashionable.”

Cold thermal relics



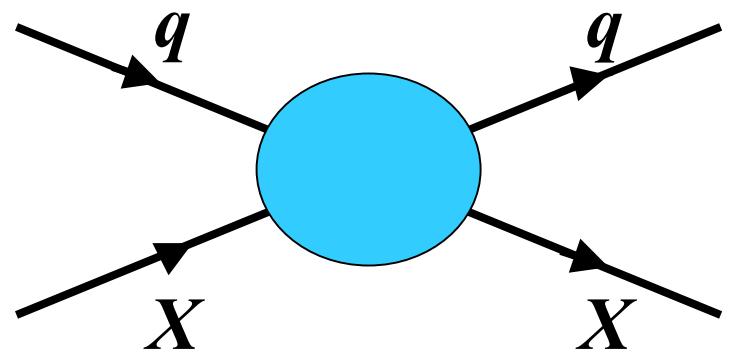
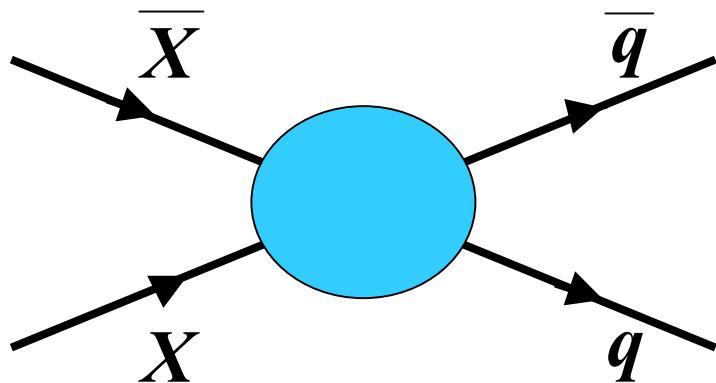
$$\Omega_X \propto \sigma_A^{-1} \quad (\text{independent of mass})$$

Cold thermal relics

$$\Omega_X h^2 \sim \langle \sigma_A v \rangle^{-1}$$

$$\sigma_A \Leftrightarrow \Omega_X$$

$$\sigma_A \Leftrightarrow \sigma_S$$



Thermal WIMP: interaction & mass limit

Ω_X depends on the annihilation strength ($\Omega_X \propto \sigma_A^{-1}$)

$\Omega_X \approx 1$ annihilation strength $\approx \frac{\text{electroweak scale}}{\text{annihilation strength} \rightarrow \text{interaction strength}}$

Possibility of direct as well as indirect detection

$\sigma_A \leq \frac{8\pi}{m_X^2}$ unitarity limit to the cross section

$$\Omega_X \leq 1 \Rightarrow M_X \leq 200 \text{ TeV}$$

**Thermal WIMP: Interaction strength determined
Mass undetermined (but < 200 TeV)**

Desperately seeking SUSY

Hierarchy problem:

- fundamental scale is Planck mass*
- particles have mass much less than Planck mass
 - gauge bosons protected by gauge symmetry
 - fermions protected by chiral symmetry
 - scalars (e.g., Higgs) defenseless!
- introduce supersymmetry to protect scalars

Supersymmetric Standard Model:

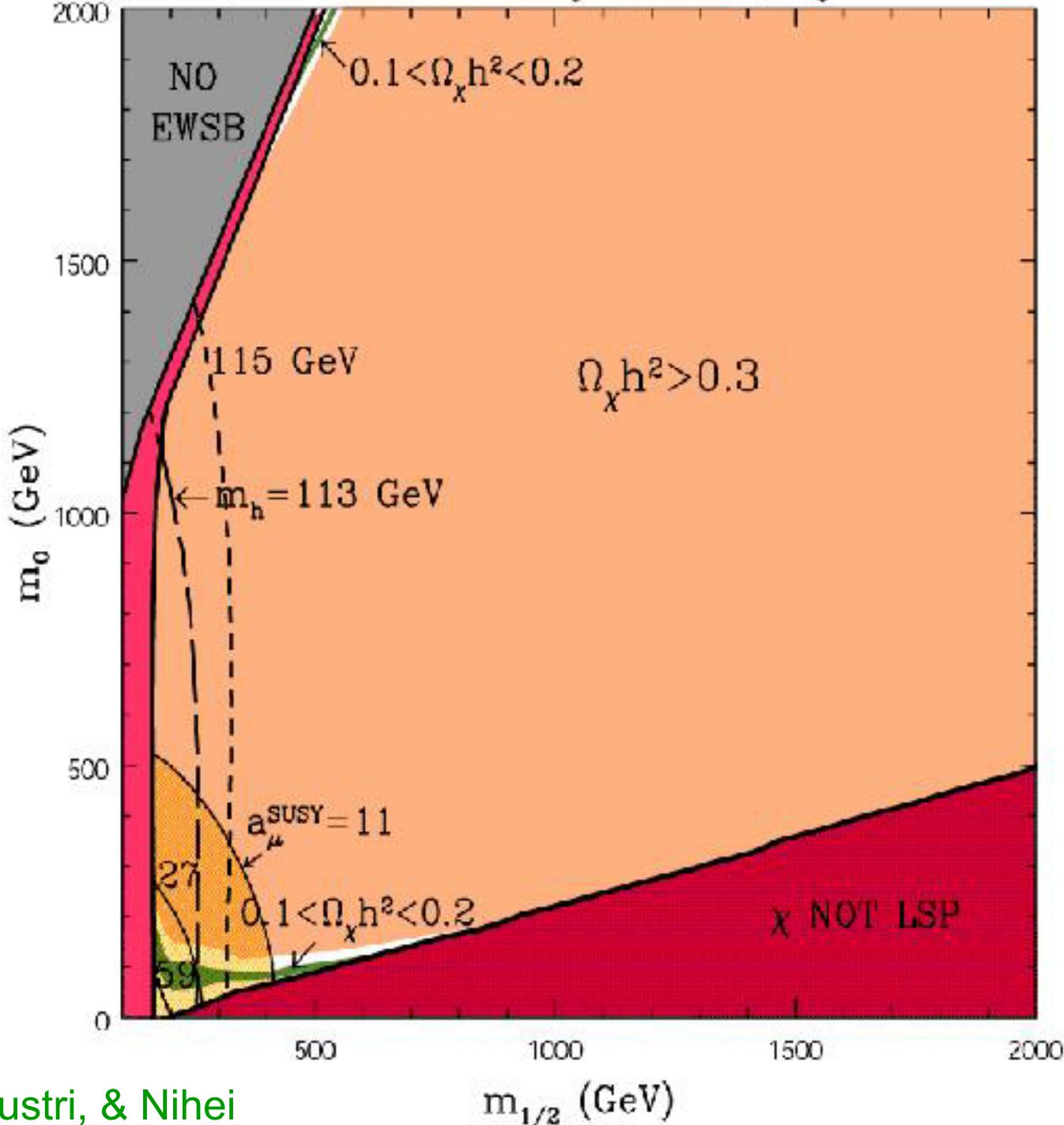
105 parameters

Constrained Minimal Supersymmetric Standard Model:

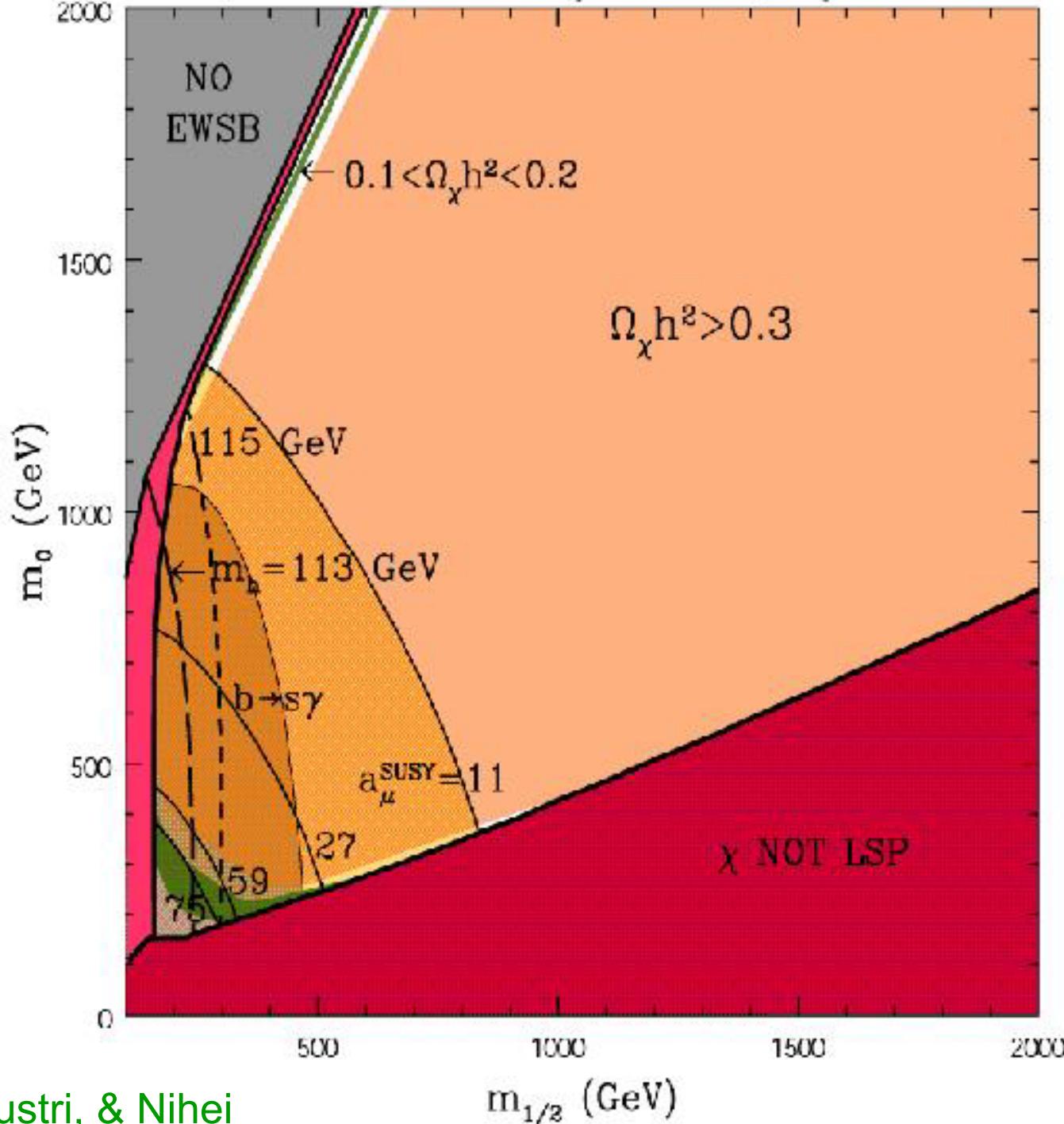
4 parameters: $\tan \beta$, $m_{1/2}$, m_0 , $\text{sign}(\mu)$

* Assumed here to be $G_N^{-1/2}$

$\tan \beta = 10$

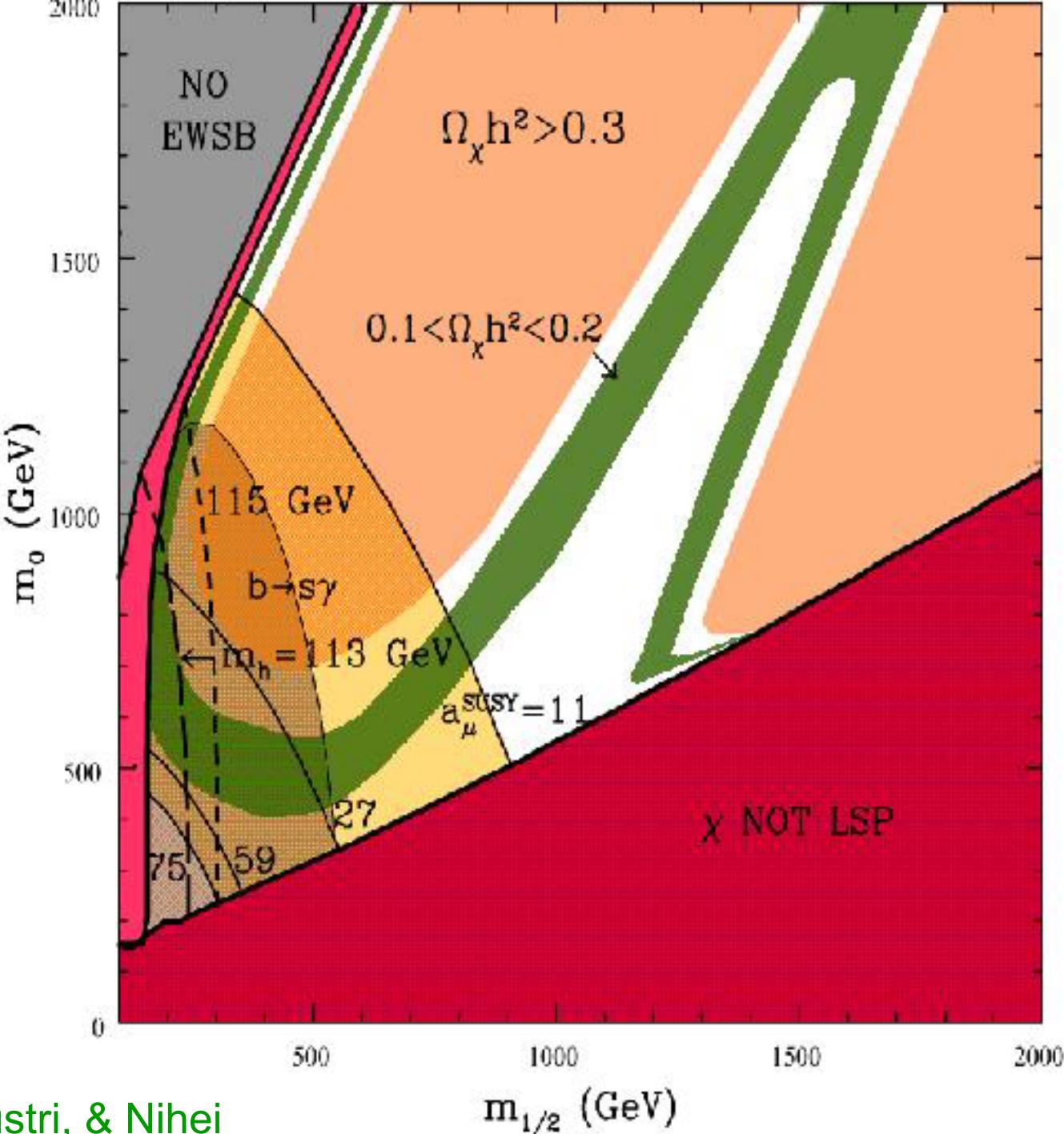


$\tan \beta = 40$

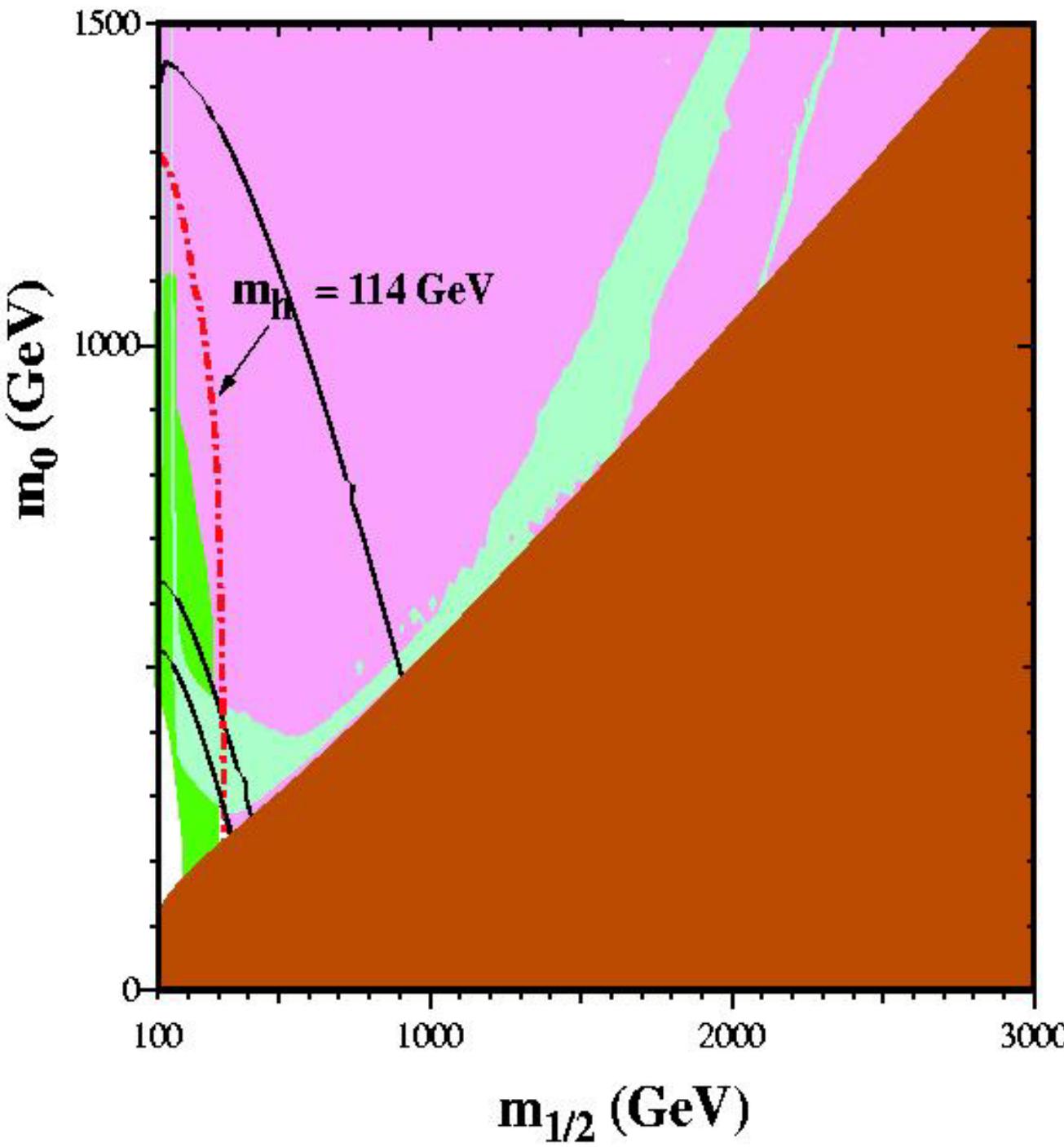


$\tan \beta = 50$

wide resonance in
neutralino annihilation



$\tan \beta = 50$



CMSSM neutralino dark matter

- SUSY not constrained, minimal, or standard
- large $\tan \beta$
 - infrared quasi-fixed point of top Yukawa coupling
 - large m_0 - focus-point region
- small $\tan \beta$
 - fine tuning for coannihilation

WIMPZILLAS

example of
non-thermal
dark matter



**SIZE
DOES
MATTER**

visit wimpzillas.com

Nonthermal dark matter

Production Mechanisms:

- Gravitational Chung, Kolb, Riotto; Kuzmin & Tkachev
- Reheating Chung, Kolb, Riotto
- Preheating Chung
- Bubble collisions Chung, Kolb, Riotto

An early particle cosmologist



**In mid-1930s, Schrödinger turned to
cosmo issues, influenced by Eddington & Lemaitre**

1938-1939: Graz → Vatican → Gent, Belgium → Dublin

The proper vibrations of the expanding universe

Erwin Schrödinger *Physica* **6**, 899 (1939)

Introduction:

“... proper vibrations [positive and negative frequency modes] cannot be rigorously separated in the expanding universe.

... this is a phenomenon of outstanding importance [WIMPZILLAS]. With particles it would mean production or annihilation of matter, merely by expansion,... Alarmed by these prospects, I have examined the matter in more detail.”

Conclusion:

“... There will be a mutual adulteration of positive and negative frequency terms in the course of time, giving rise to ... the ‘alarming phenomenon’...”

The proper vibrations of the expanding universe

Erwin Schrödinger *Physica* **6**, 899 (1939)

Creation of a single pair of particles

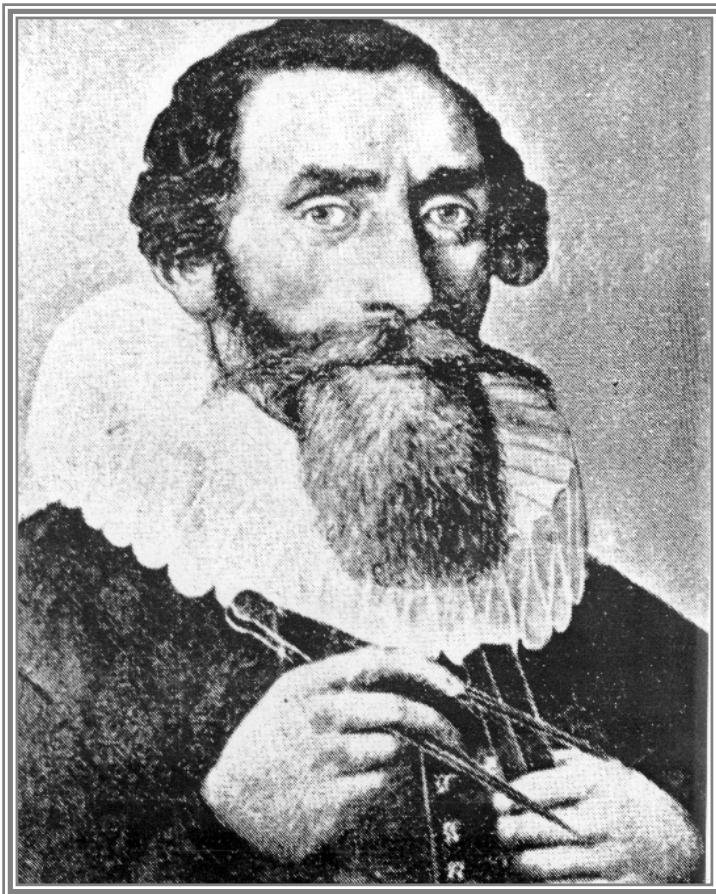
per Hubble volume $V_H \simeq 10^{57} \text{ km}^3$

per Hubble time $t_H \simeq 10^{10} \text{ years}$

with “Hubble energy” $E_H \simeq 10^{-33} \text{ eV}$

Alarming?

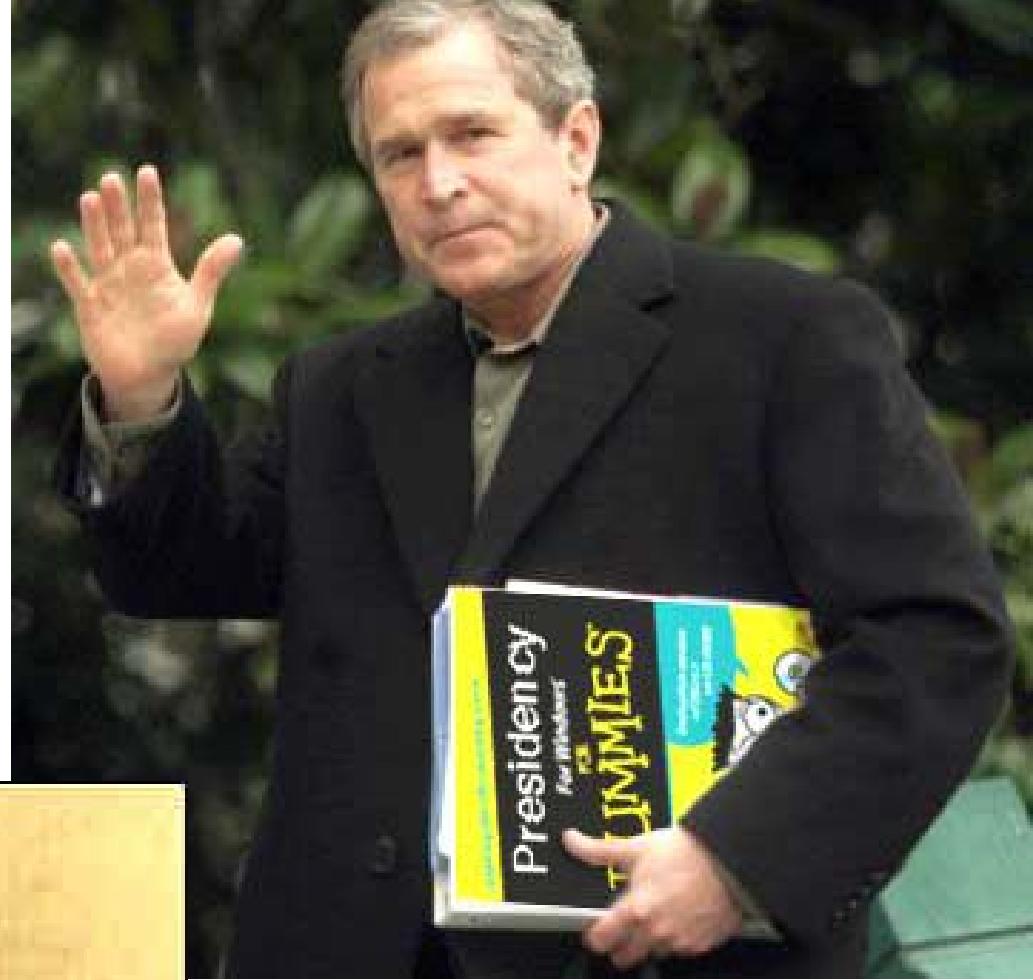
An even earlier Graz cosmologist



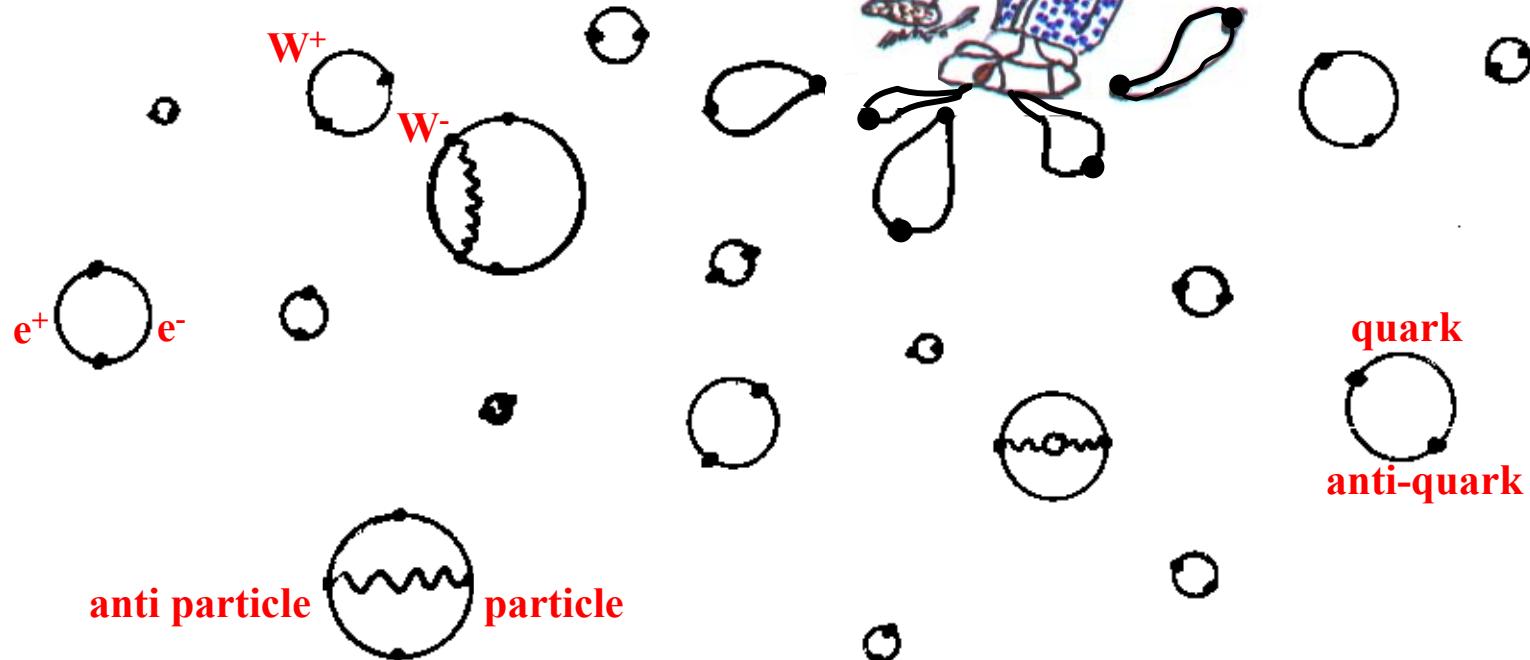
“When the storms rage around us, and the state is threatened by shipwreck, we can do nothing more noble than to lower the anchor of our peaceful studies in the ground of eternity.” - *J. Kepler*

1600-1630: Graz → Prague → Linz → Sagan → Ratisbon

“When the storms rage
around us, and the state
is threatened by shipwreck,
.....



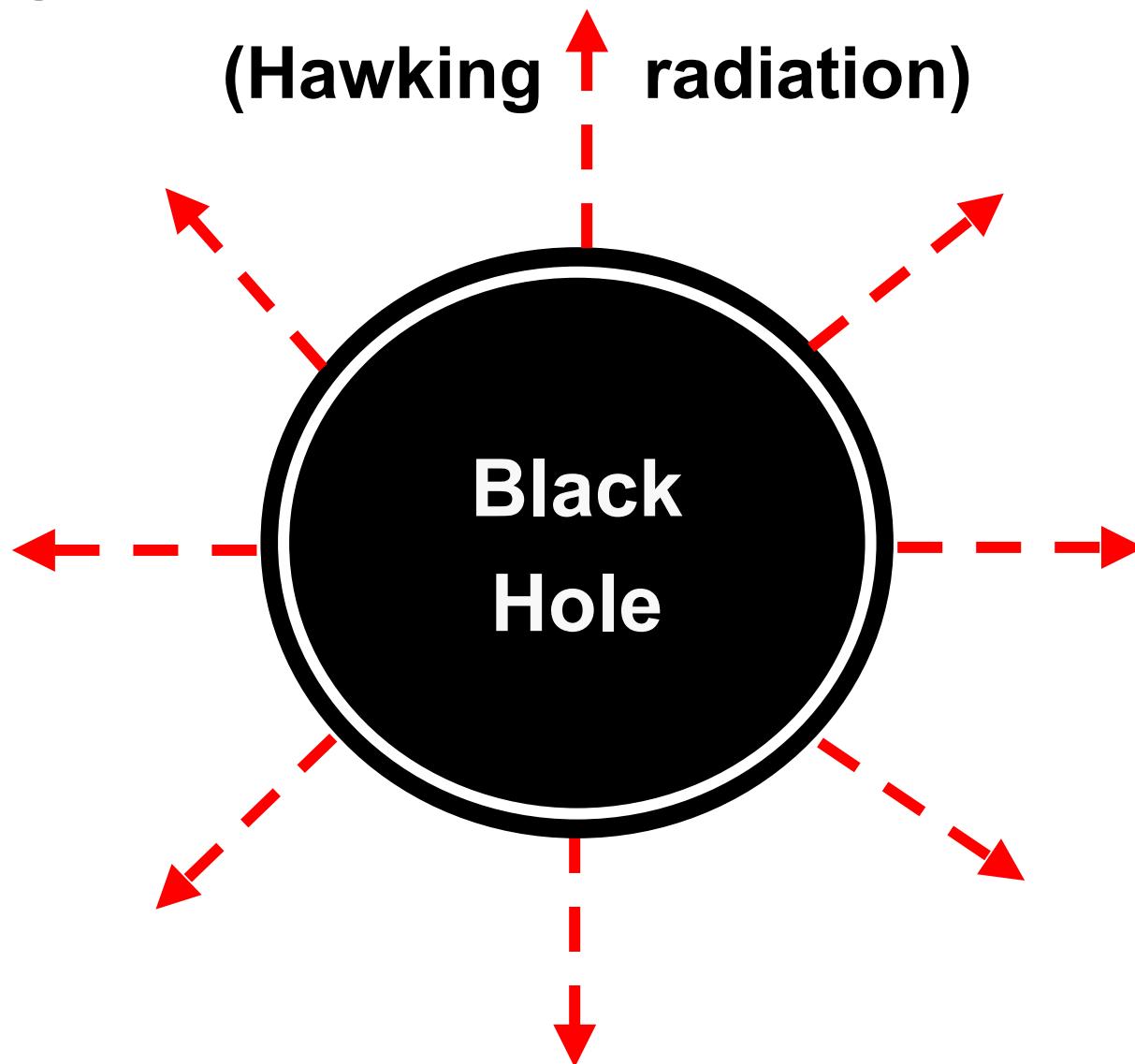
The Vacuum



Quantum Uncertainty

Disturbing the vacuum

Strong gravitational field → particle production



Expanding universe → particle creation

Arnowit, Birrell, Bunch, Davies, Deser, Ford, Fulling, Grib, Hu, Kofman, Lukash, Mostepanenko, Page, Parker, Starobinski, Unruh, Vilenkin, Wald, Zel'dovich,...

It's not a bug, it's a feature!

first application: { density perturbations from inflation
gravitational waves from inflation

(Guth & Pi; Starobinski; Bardeen, Steinhardt, & Turner; Hawking; Rubakov; Fabbi & Pollack; Allen)

new application: **dark matter**

(Chung, Kolb, & Riotto; Kuzmin & Tkachev)

- require (super)massive particle “X”
- stable (or at least long lived)
- initial inflationary era followed by radiation/matter

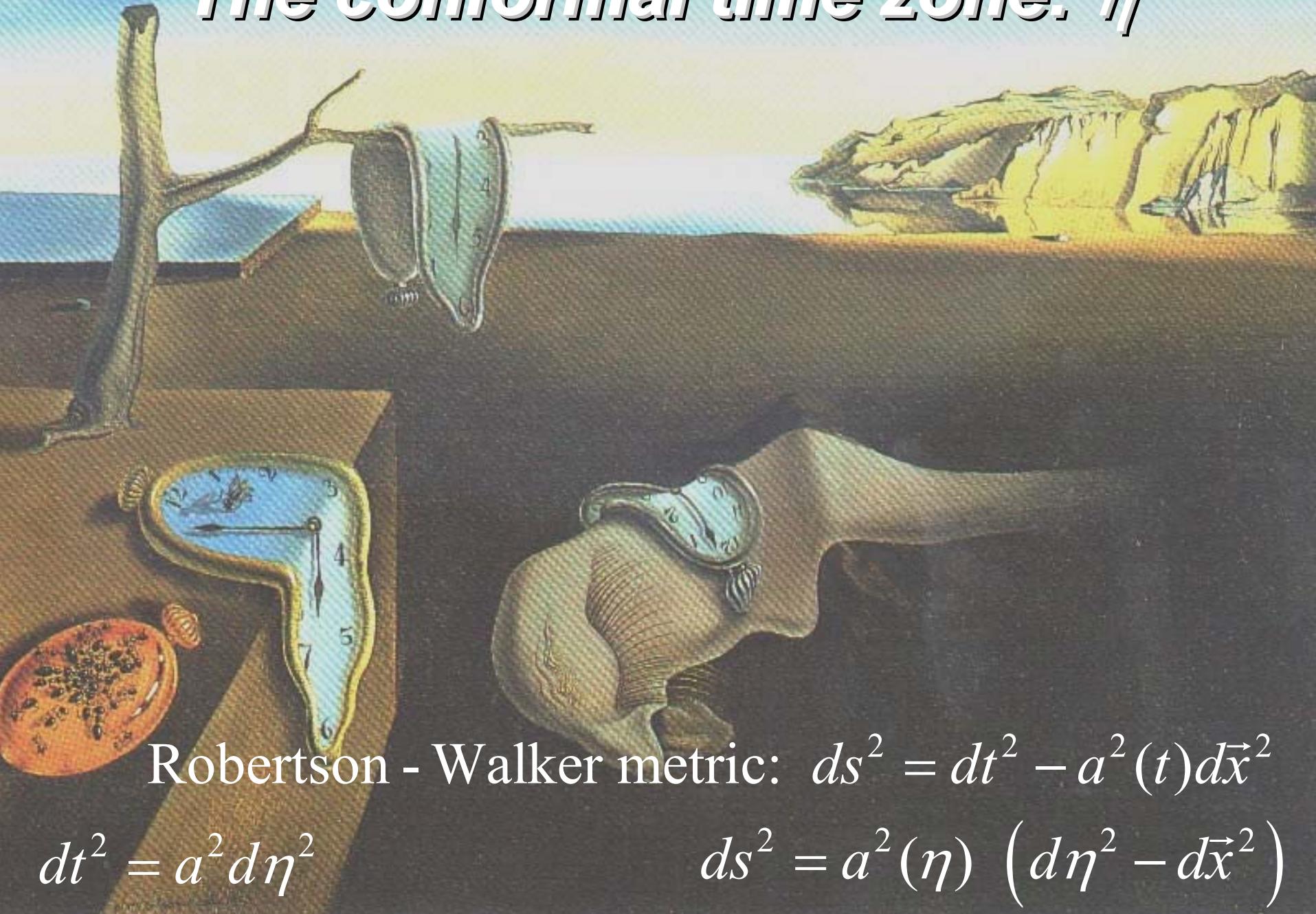
Scalar field X of mass M_X

Fourier modes [$a(\eta)$ = expansion scale factor]

$$X(\vec{x}, \eta) = \int \frac{d^3x}{(2\pi)^{3/2} a(\eta)} \left[a_k h_k(\eta) e^{i\vec{k} \cdot \vec{x}} + a_k^\dagger h_k^*(\eta) e^{-i\vec{k} \cdot \vec{x}} \right]$$

$(\eta = \text{conformal time})$

The conformal time zone: η



Robertson - Walker metric: $ds^2 = dt^2 - a^2(t)d\vec{x}^2$

$$dt^2 = a^2 d\eta^2$$

$$ds^2 = a^2(\eta) \left(d\eta^2 - d\vec{x}^2 \right)$$

Scalar field X of mass M_X

Fourier modes [$a(\eta)$ = expansion scale factor]

$$X(\vec{x}, \eta) = \int \frac{d^3x}{(2\pi)^{3/2} a(\eta)} \left[a_k h_k(\eta) e^{i\vec{k}\cdot\vec{x}} + a_k^\dagger h_k^*(\eta) e^{-i\vec{k}\cdot\vec{x}} \right]$$

Mode equation (η = conformal time)

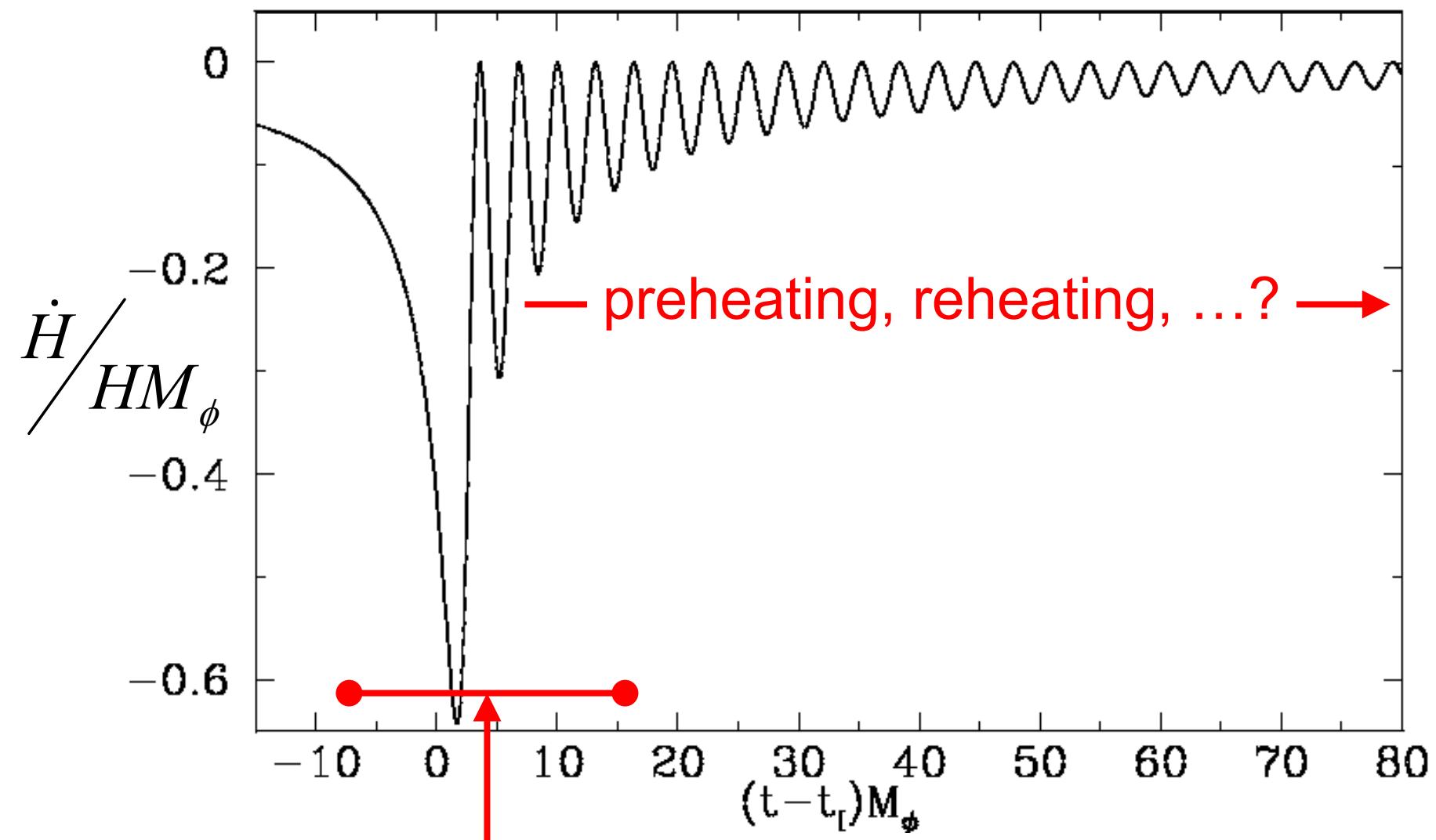
$$h_k''(\eta) + \left[k^2 + M_X^2 a^2 + (6\xi - 1) \overset{\text{0}}{\cancel{a''/a}} \right] h_k(\eta) = 0$$

$$h_k''(\eta) + \omega_k^2 h_k(\eta) = 0$$

Particle creation in nonadiabatic region

measure of nonadiabaticity $\propto \frac{\omega'_k}{\omega_k}$ or $\frac{\dot{H}}{H^2}$

Background fields in chaotic inflation



nonadiabatic region: particle creation

No-particle state in past

$$a_k^0 |0\rangle = 0 \quad h_k^0 \leftrightarrow a_k^0$$

$h_k(\eta)$ adulterated as $\omega_k(\eta)$ changes

$$h_k = \alpha_k h_k^0 + \beta_k h_k^{0*}$$

$$a_k = \alpha_k a_k^0 - \beta_k a_k^{0+}$$

Particle creation

$$N_k = \langle 0 | a_k^+ a_k^- | 0 \rangle \propto |\beta_k|^2$$

Solve wave equation

$$h_k''(\eta) + \omega_k^2(\eta) h_k(\eta) = 0$$

$$\omega_k^2(\eta) = k^2 + M_X^2 a^2(\eta)$$

$$h_k^0 = 1/\sqrt{2\omega_k^0} \quad h_k'^0 = -i\sqrt{\omega_k^0/2}$$

Find Bogoliubov coefficient

$$|\beta_k|^2 = \frac{|h_k'|^2 + \omega_k^2 |h_k|^2 - \omega_k}{2\omega_k}$$

Number density proportional to

$$\int_0^\infty \frac{dk}{2\pi^2} k^2 |\beta_k|^2$$

Particle production

Field theory : the result is almost always *infinite!*

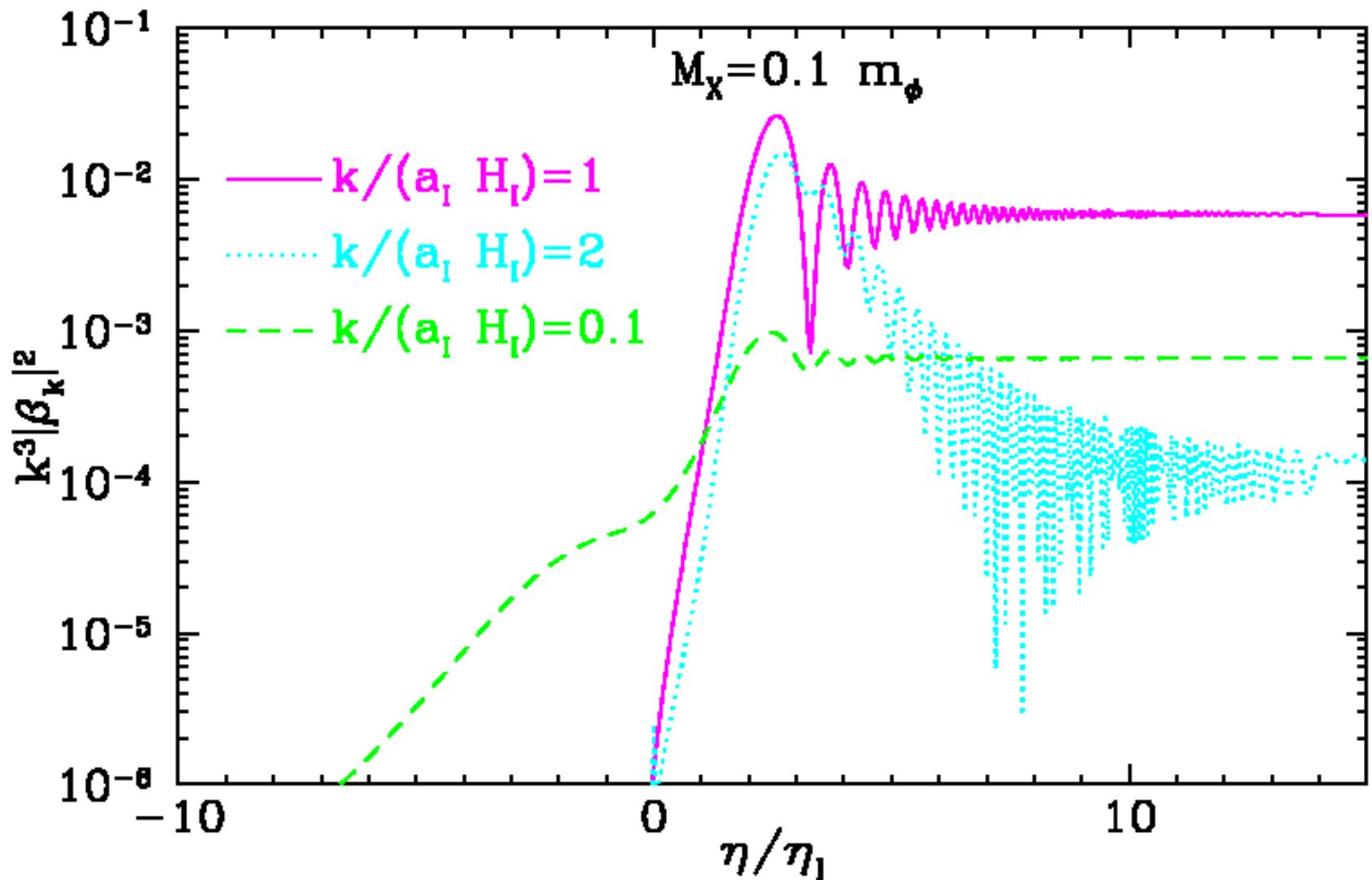
finite result if $\frac{d^n}{d\eta^n} \left[\frac{1}{a^2(\eta)} \frac{da^2(\eta)}{d\eta^2} \right]$ **finite**

inflation $a \propto e^{H_I t}$	$a^2(\eta) \propto \eta^{-2}$ $-\infty < \eta < 0$ $0 < t < +\infty$	fails at $\eta = 0$ $t = +\infty$
matter/ radiation $a \propto t^{2/3}, t^{1/2}$	$a^2(\eta) \propto \eta^2, \eta$ $0 < \eta < +\infty$ $0 < t < +\infty$	fails at $\eta = 0$ $t = 0$

start in inflation, end in matter/radiation

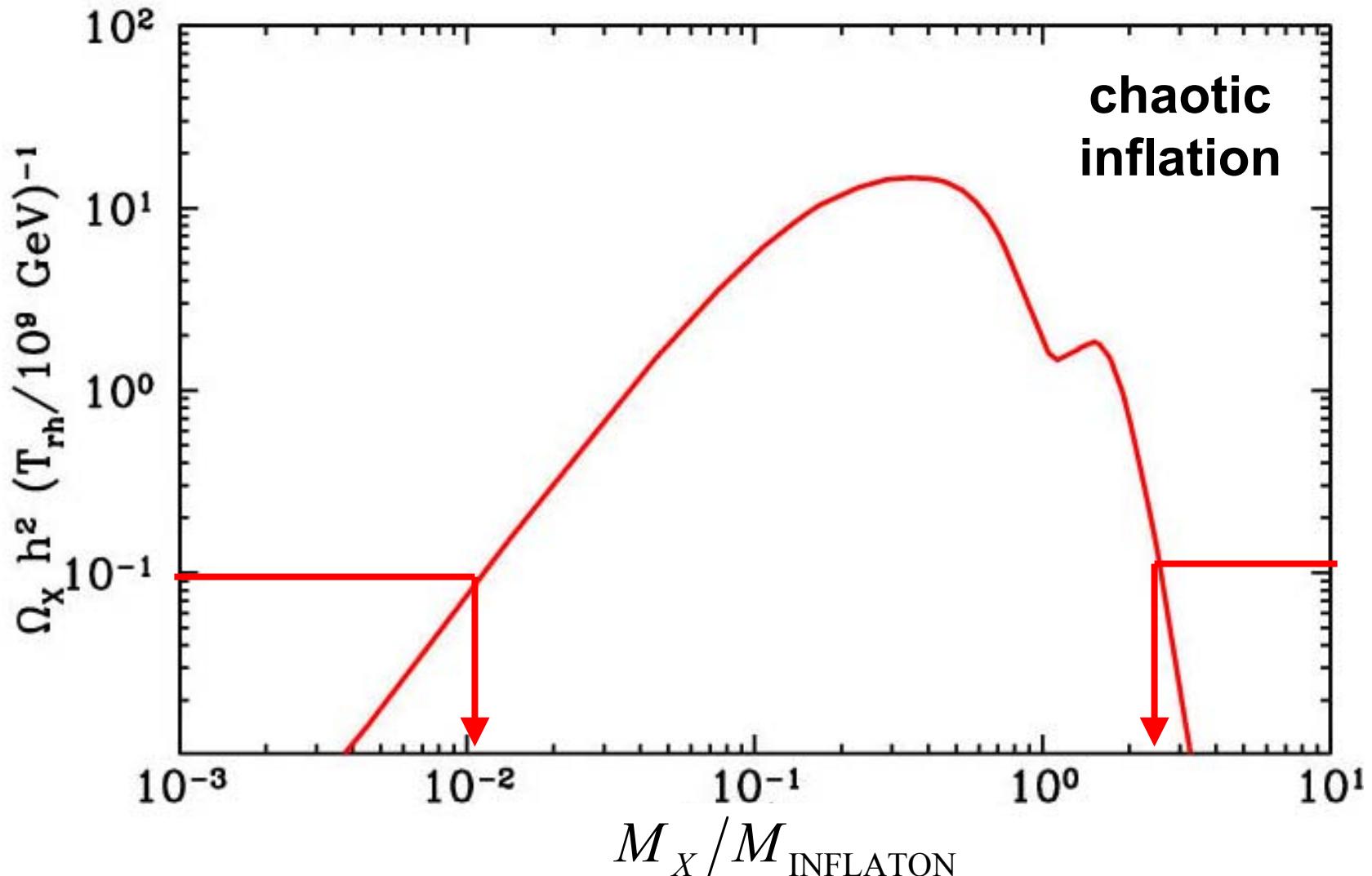
Particle production

$$\eta/\eta_I \sim 1 \quad k \sim aH$$



Particle production

Chung, Kolb, Riotto (also Kuzmin & Tkachev)



$$\Omega_X \approx 1 \quad \text{for} \quad M_X / M_{\text{INFLATON}} \approx 1 \Rightarrow M_X \approx 10^{10} \text{ to } 10^{15} \text{ GeV}$$

Superheavy particles

Inflaton mass (in principle measurable from gravitational wave background, guess 10^{12} GeV) may signal a new mass scale in nature.

Other particles may exist with mass comparable to the inflaton mass.

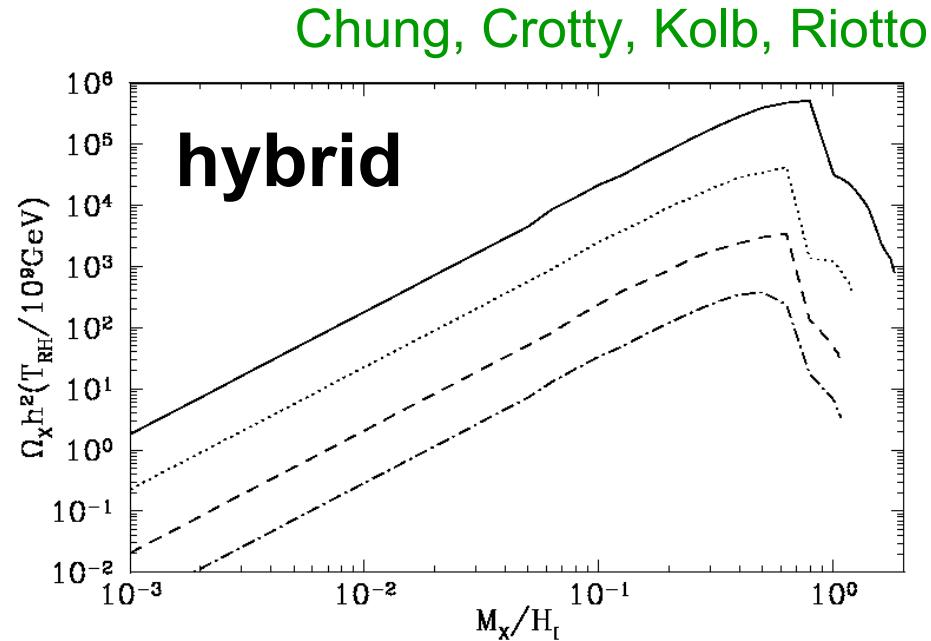
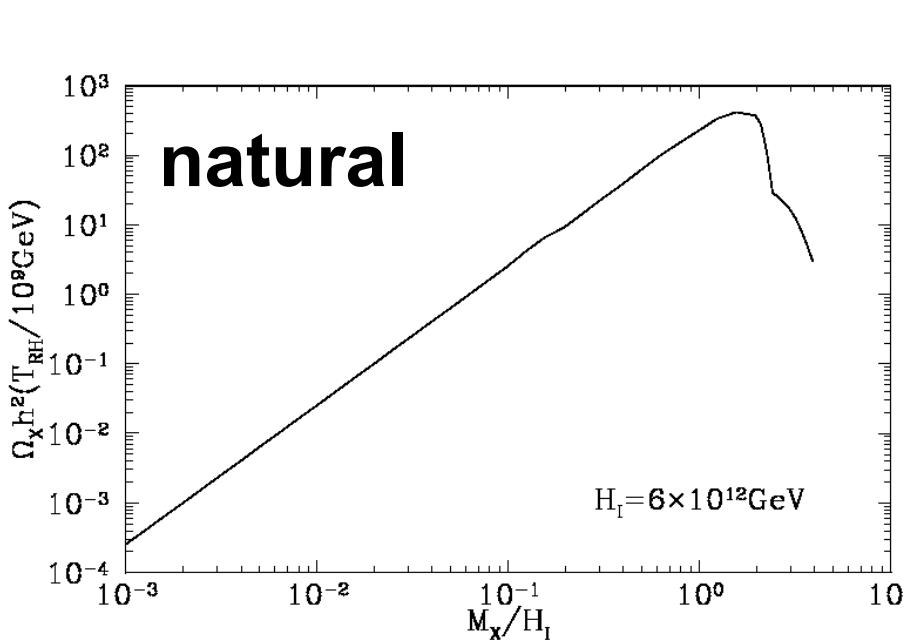
Conserved quantum numbers may render the particle stable.

Model exploration

Gravitational Production:

- Fermions Kuzmin & Tkachev
- Non-conformal couplings Kuzmin & Tkachev
- Small-field models Crotty, Chung, Kolb, Riotto
- Hybrid models Crotty, Chung, Kolb, Riotto

Model exploration



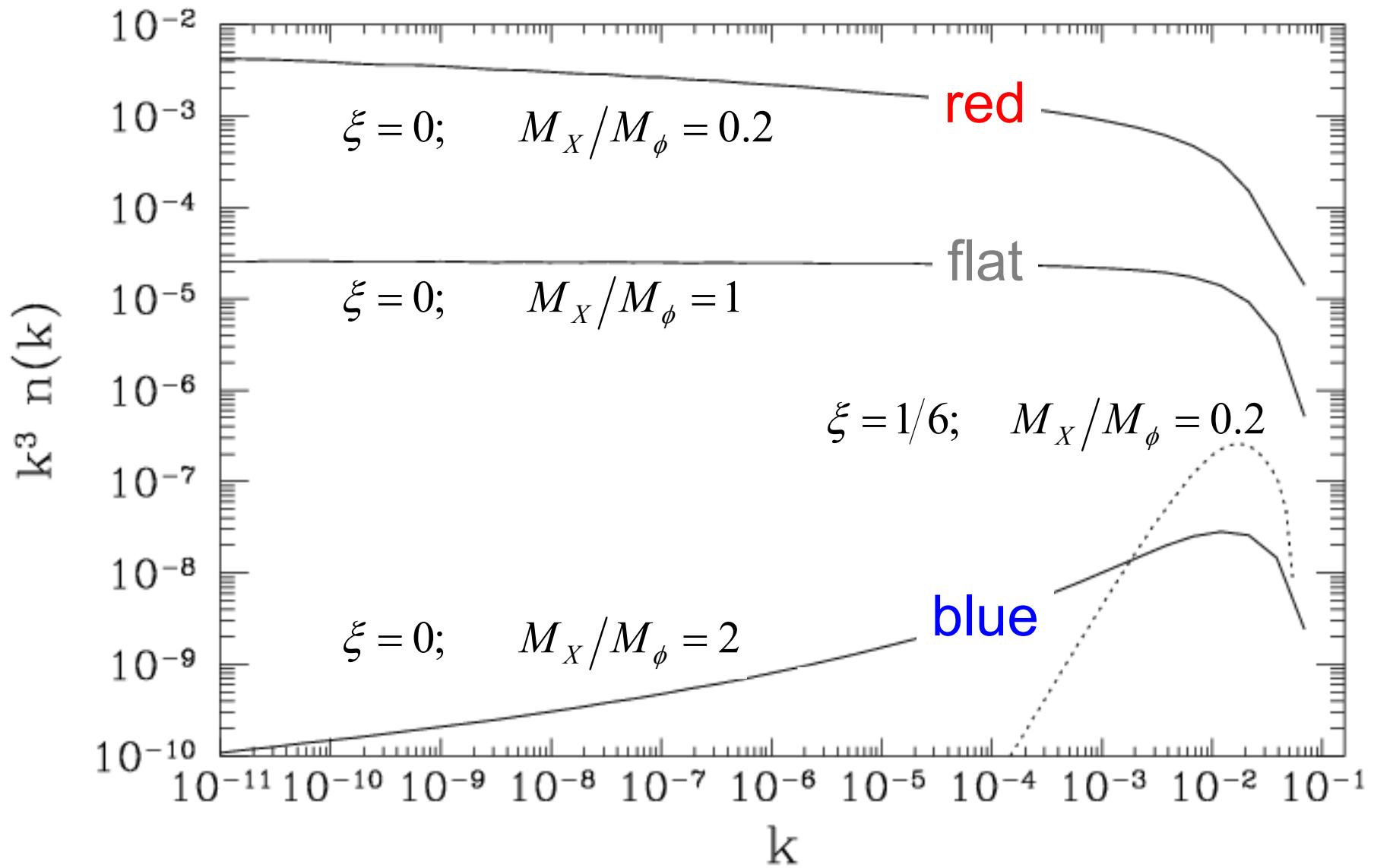
$$M_X \leq H_I \rightarrow \Omega_X h^2 \approx \left(\frac{M_X}{10^{11} \text{ GeV}} \right)^2 \left(\frac{T_{RH}}{10^9 \text{ GeV}} \right)$$

$$M_X \geq H_I \rightarrow \Omega_X h^2 \propto \exp(-M_X/H_I)$$

Isocurvature modes

Kuzmin & Tkachev

Chung, Kolb, Riotto, Senatore



Wimpzilla characteristics:

- supermassive: $10^9 - 10^{19}$ GeV ($\sim 10^{12}$ GeV ?)
- abundance may depend only on mass
- abundance may be independent of interactions
 - sterile?
 - electrically charged?
 - strong interactions?
 - weak interactions?
- unstable (lifetime > age of the universe)?

WIMPZILLA footprints:



Isocurvature modes:

CMB, Large-scale structure

Decay:

Ultra High Energy Cosmic Rays

Annihilate:

Galactic Center, Sun

Direct Detection:

Bulk, Underground Searches

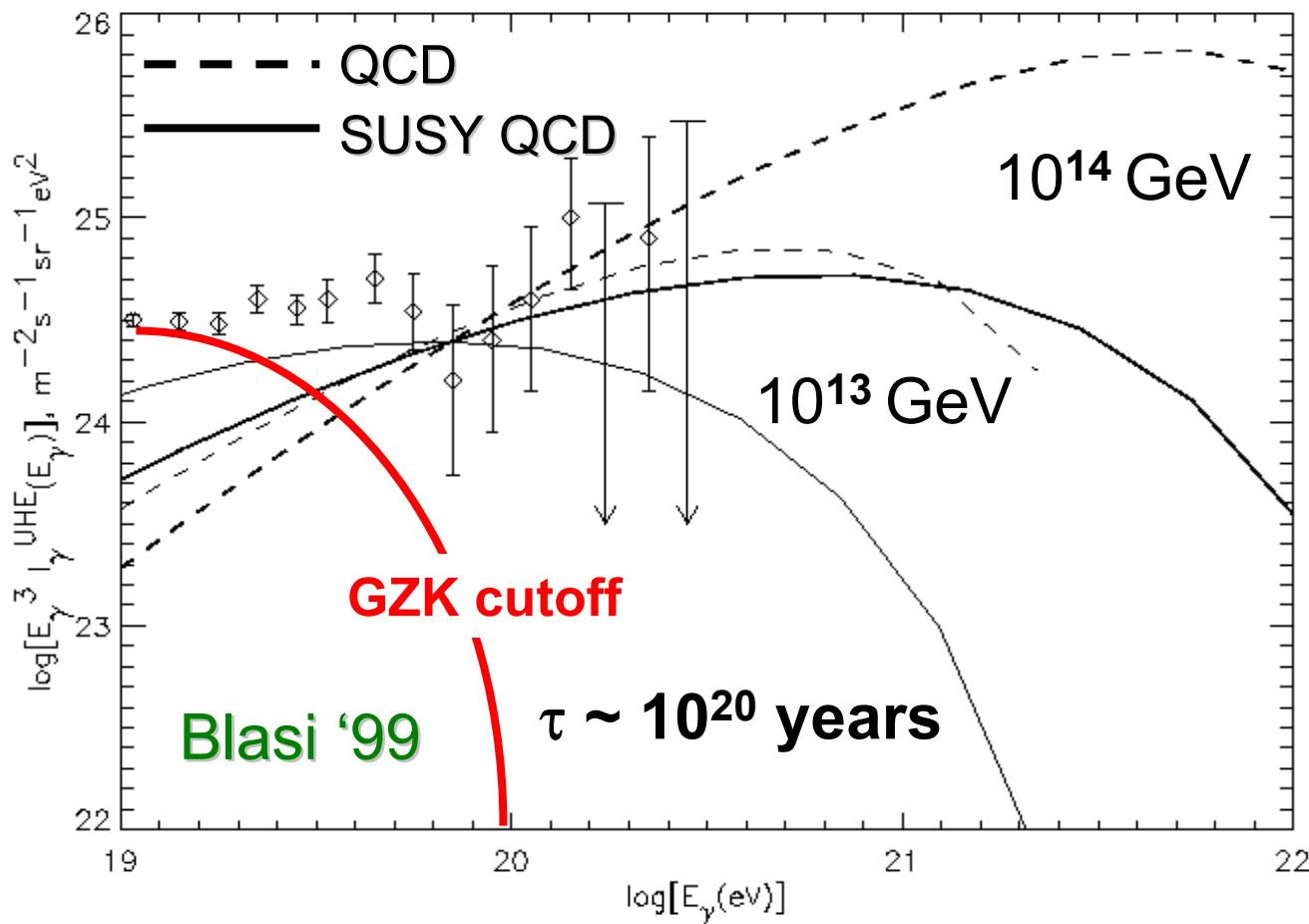
WIMPZILLA decay

X → UHE cosmic rays

$$10^{13} \text{ GeV} = 10^{22} \text{ eV}$$

Kuzmin & Rubakov; Birkel & Sarkar;
Ellis, Gelmini, Lopez, Nanopoulos & Sarkar;
Berezinsky, Kachelriess, & Vilenkin;
Benakli, Ellis, & Nanopoulos; Berezinsky, Blasi, & Vilenkin;
Blasi; Berezinsky & Mikhajlov;
Dubovsky & Tinyakov; Medina-Tanco & Watson;
Blasi & Seth; Ziaeepour; Crooks, Dunn, & Frampton

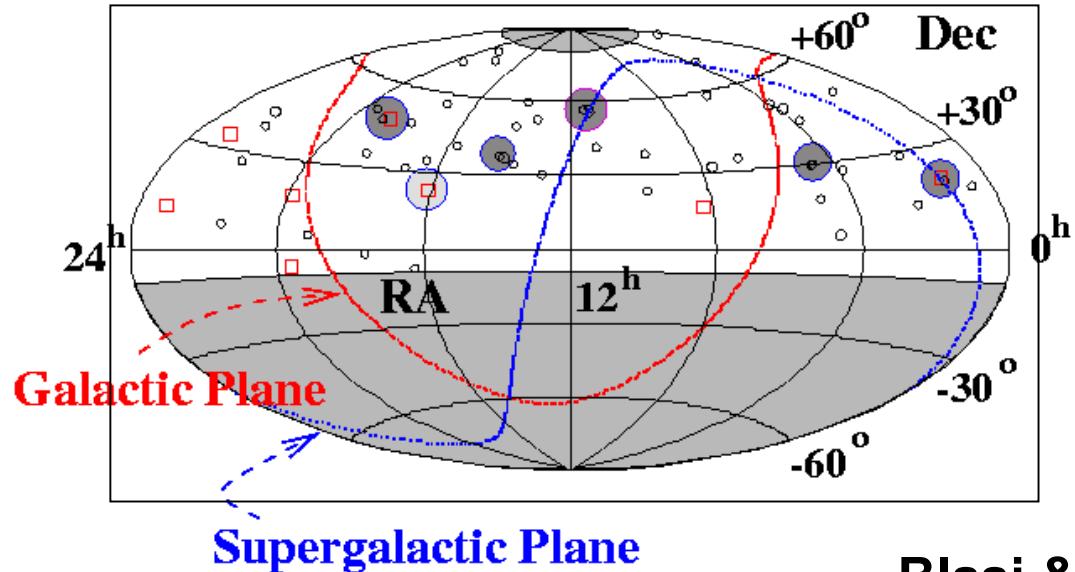
WIMPZILLA decay



UHE cosmic rays mostly photons; characteristic spectrum;
UHE neutrinos; lower-energy crud;
clumping → anisotropies

Clustering of UHE events

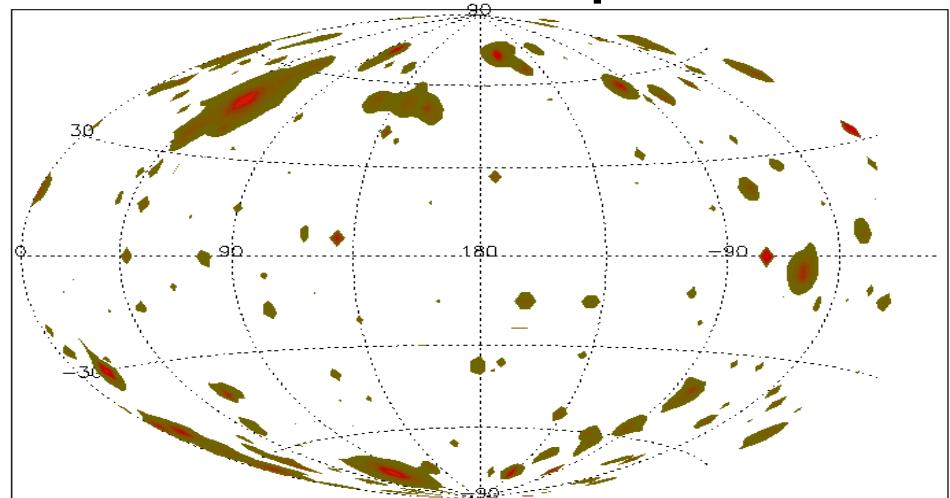
UHE cosmic rays



probability from
isotropic distribution:
 $<1\%$

model follows Navarro,
Frenk, White dark matter
distribution

Blasi & Sheth astro-ph/0006316



WIMPZILLA annihilation

- **WIMPZILLAS collect in galactic center**

$XX \rightarrow$ photons, antiprotons, positrons

Bertone, Silk, Sigl astro-ph/0011553

$XX \rightarrow$ UHE cosmic rays

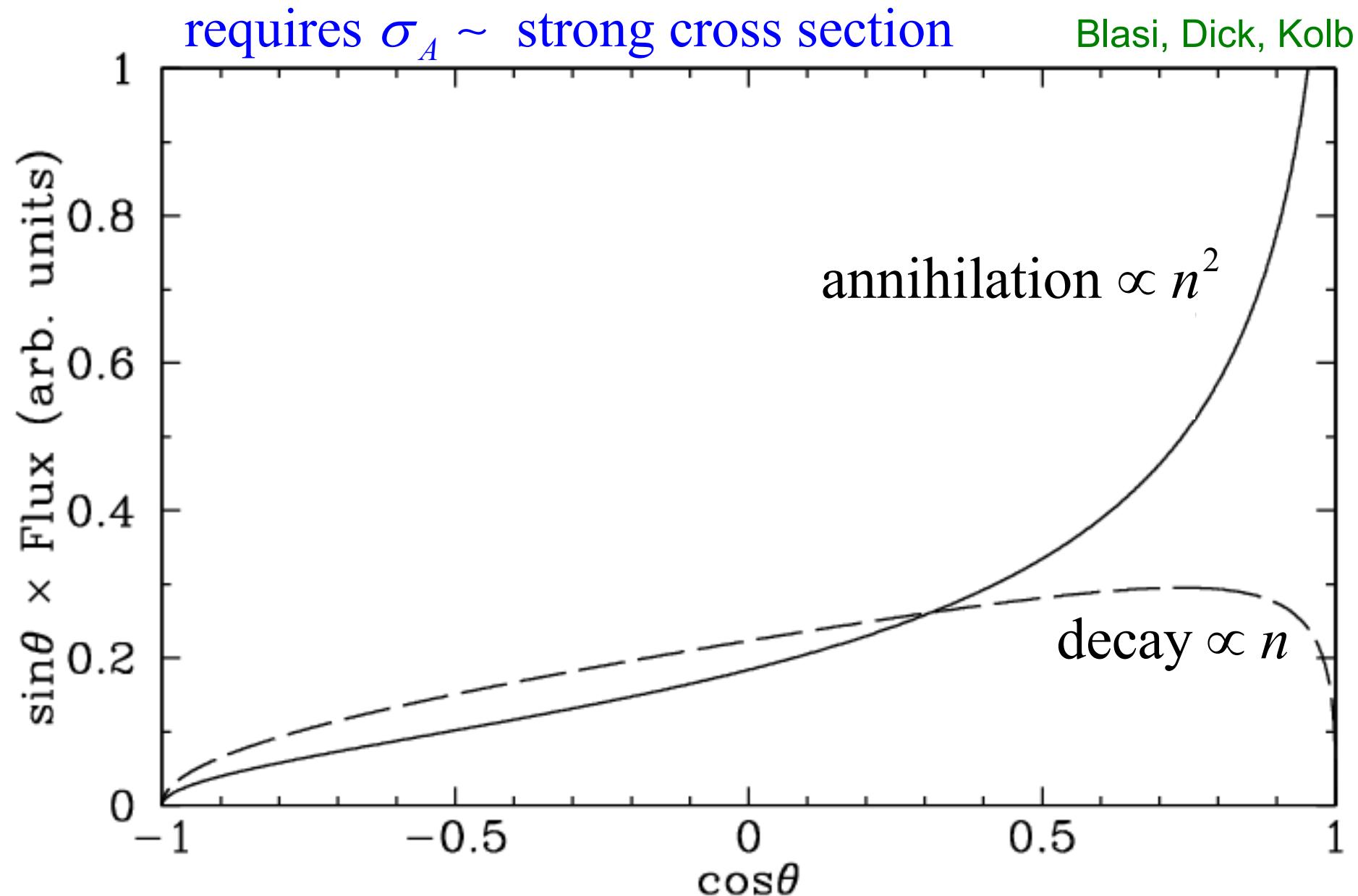
Blasi, Dick, Kolb astro-ph/yymmnnn

- **WIMPZILLAS collect in sun**

$XX \rightarrow$ neutrinos

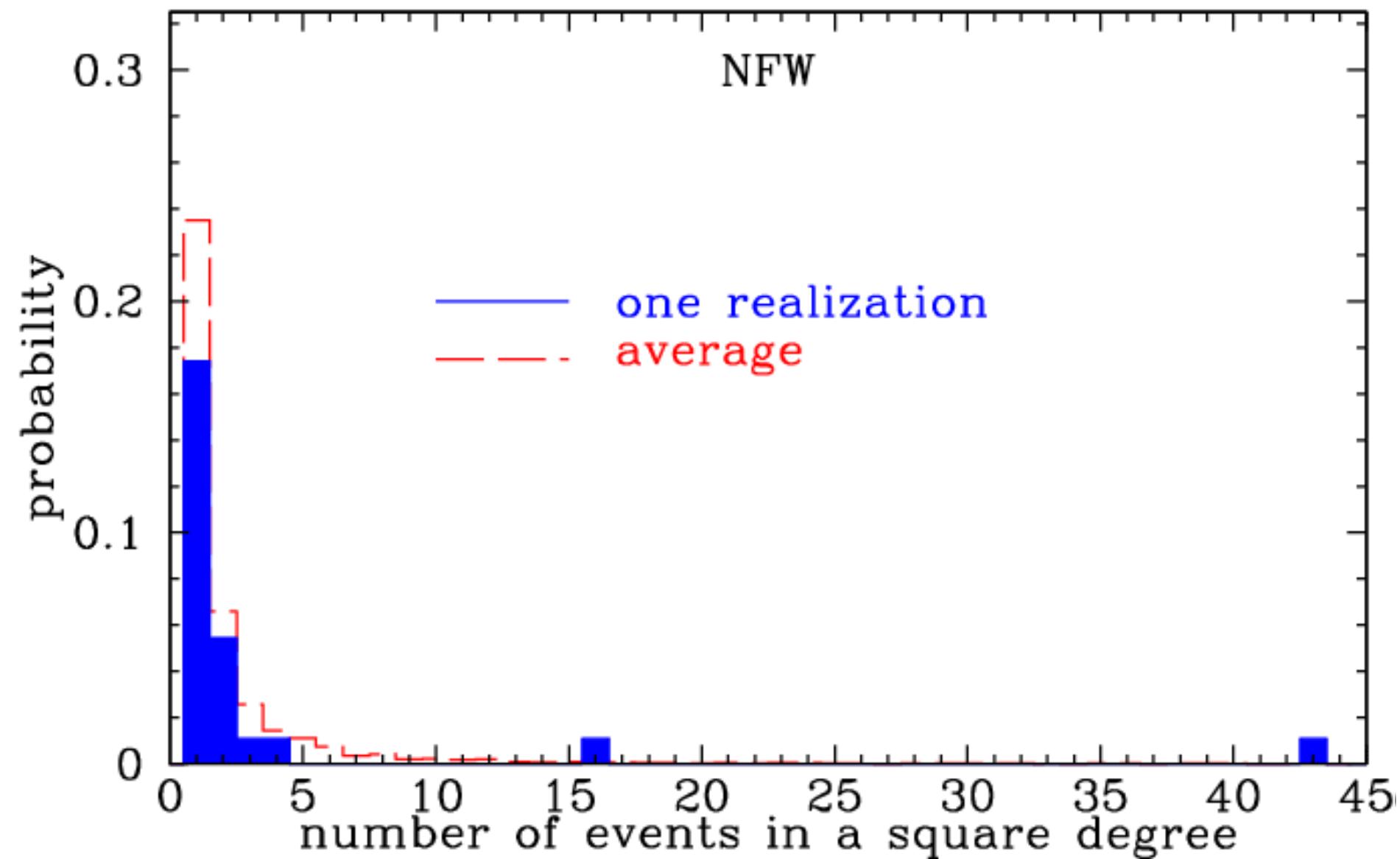
Albuquerque, Hui, Kolb hep-ph/0009017

UHE events from galactic center



Annihilation from subclumps

Blasi, Dick, Kolb



Capture in the sun

Press & Spergel; Gould;

Wimpzilla of mass $M = 10^{12} M_{12} \text{GeV}$

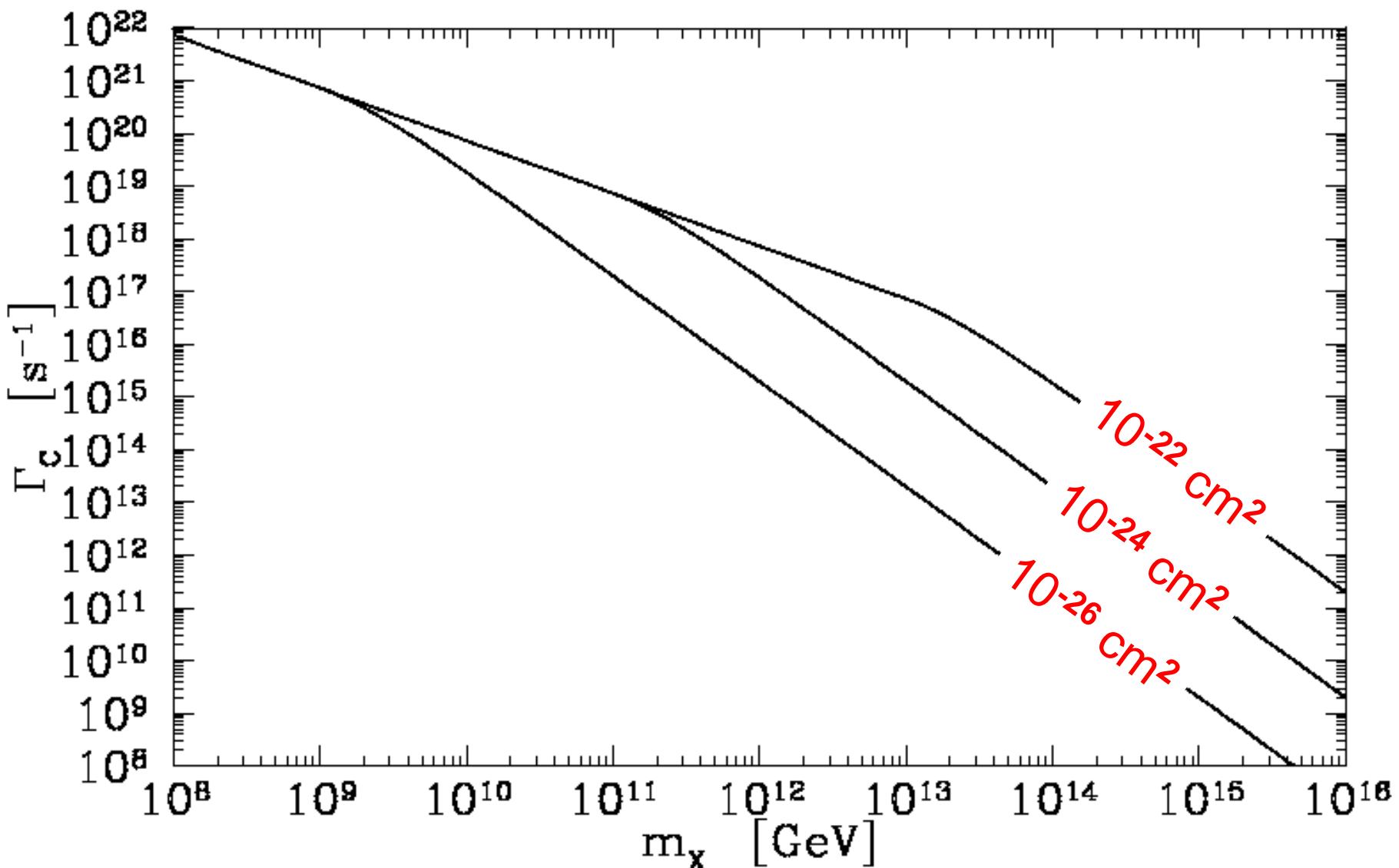
$$\rho = 0.3 \text{ GeV cm}^{-3} \quad \rightarrow \quad n = 3 \times 10^{-13} M_{12}^{-1} \text{ cm}^{-3}$$

$$v = 244 \text{ km s}^{-1} \quad \rightarrow \quad F = 6 \times 10^{-7} M_{12}^{-1} \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$$

$$A_{SUN} = 6 \times 10^{22} \text{ cm}^2 \quad \rightarrow \quad 4 \times 10^{16} M_{12}^{-1} \text{ s}^{-1} \text{ hit sun}$$

But they gotta stick!

Capture in the sun



Sticking in the sun

Hit the sun: $v = v_{escape}$

- initial kinetic energy = $10^6 M_{12} \text{GeV}$

Scatter in the sun: $\sigma = 10^{-24} \sigma_{-24} \text{cm}^2$

- # collisions = $10^{12} \sigma_{-24}$
- energy loss = $m_{proton} v^2$ per collision
- energy loss = $10^6 \sigma_{-24} \text{ GeV}$ through sun

Most captured if $\sigma_{-24}/M_{12} \geq 1$

Otherwise, capture only low-velocity tail

Sinking SIMPZILLAS

Strongly interacting w/IMPZILLA = SIMPZILLA

Massive \rightarrow small velocity \rightarrow sink

Initial configuration thermally supported

$$N \approx 10^{26} \quad r \approx 50 \text{ meters}$$

Then collapse

- Self gravitating or large nucleus?
- Black hole?
- Sufficient annihilation to reach equilibrium

$$N \approx 10^{30} \quad r \approx 10^{-4} \text{ cm}$$

$$\Gamma_A = \Gamma_C$$

Fragmentation



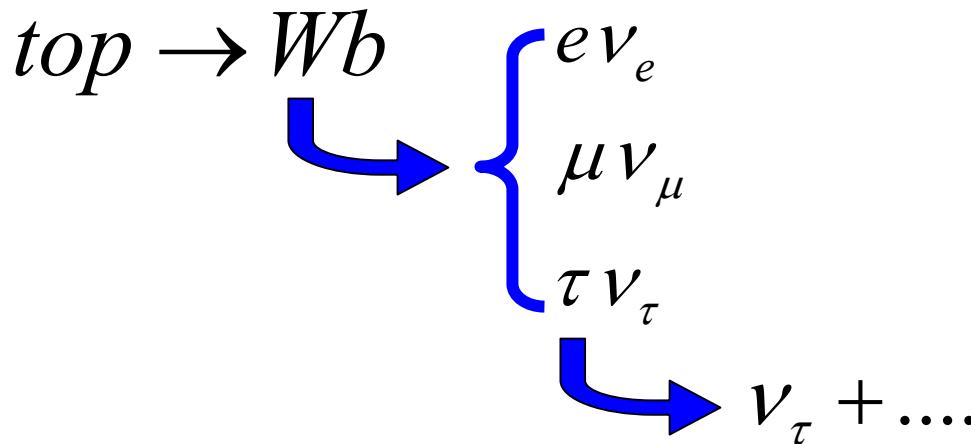
$$N_H = 7 \times 10^6 M_{12}^{1/2}$$

$$N_c = 2 \times 10^6 M_{12}^{1/2}$$

$$N_b = 1 \times 10^6 M_{12}^{1/2}$$

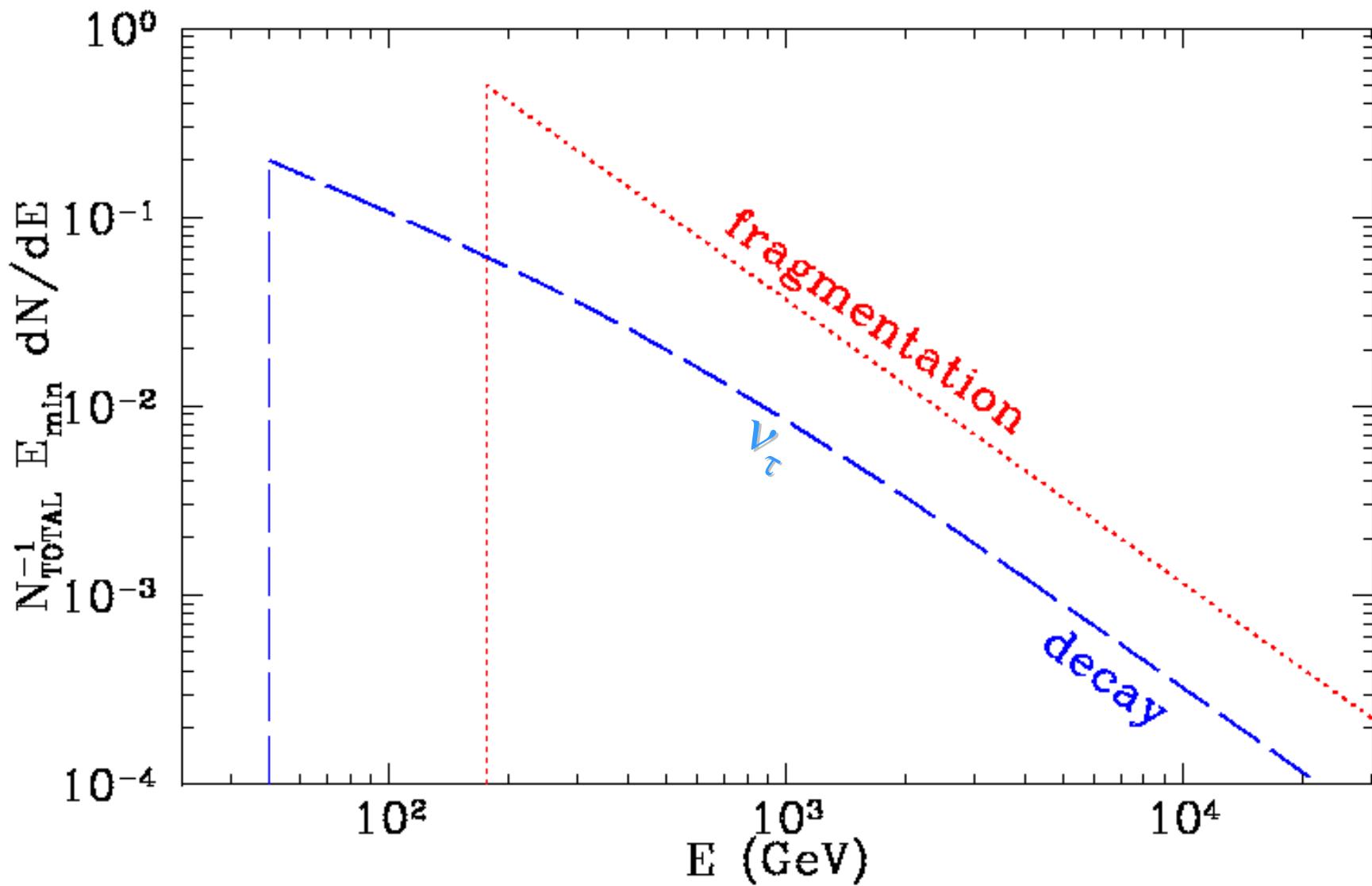
$$N_t = 3 \times 10^5 M_{12}^{1/2}$$

Decay



each annihilation produces $10^4 M_{12}^{1/2} \nu_\tau$'s

Fragmentation & decay spectra

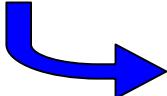


Neutrino scattering

$\nu_e \rightarrow \cancel{e^+} + \dots$ e and μ absorbed \rightarrow

$\nu_\mu \rightarrow \cancel{\mu^+} + \dots$ ν_e and ν_μ absorbed*

$\nu_\tau \rightarrow \tau^+ + \dots$

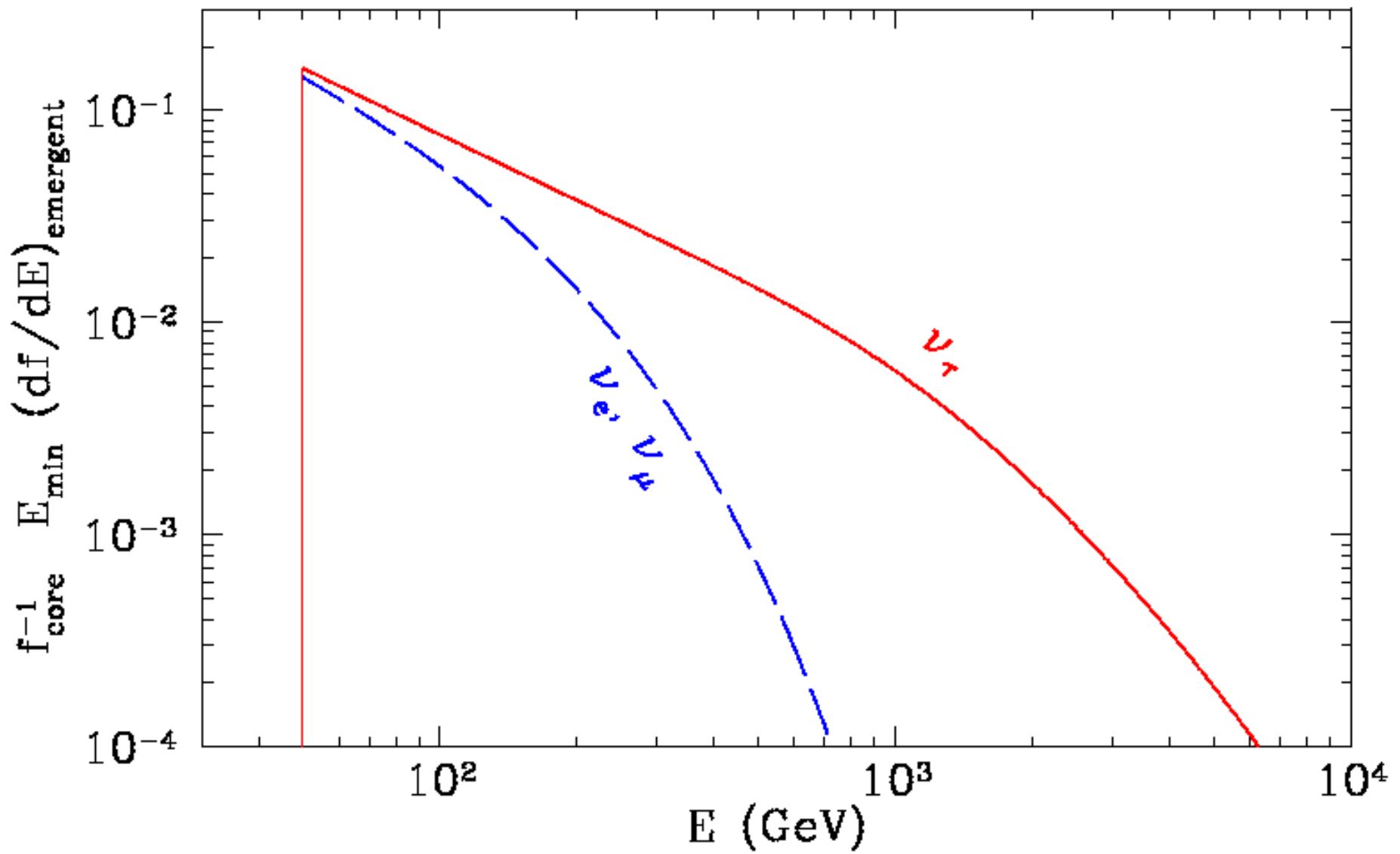
 $\nu_\tau + \dots$

ν_τ emerges as lognormal distribution centered at transparency energy (Halzen & Saltzberg)

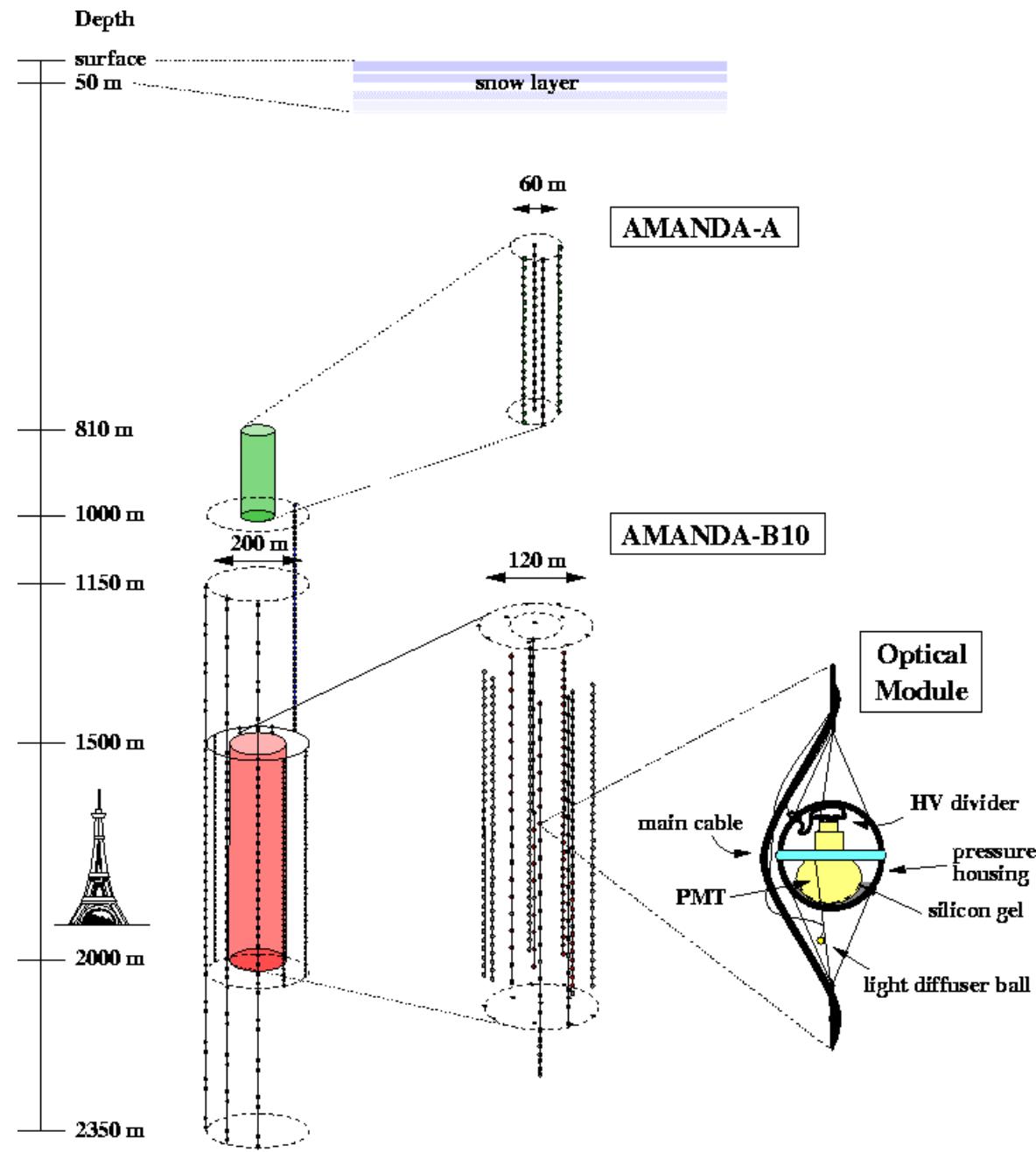
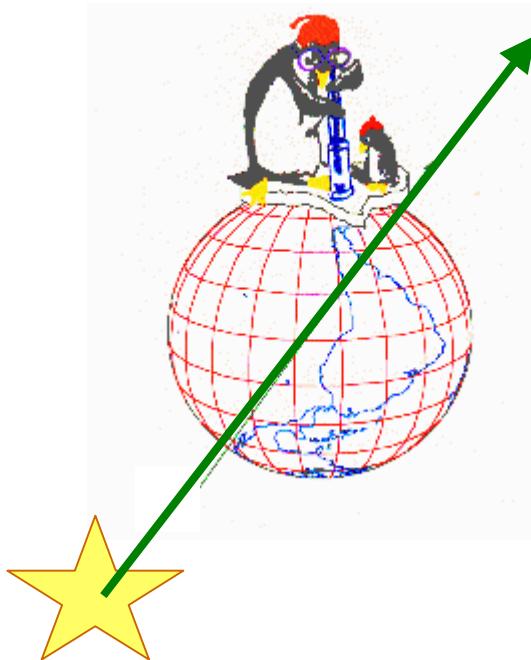
Transparency energy: $E_\kappa = 150$ GeV

* except for ν_e and ν_μ produced in 'last' interactions

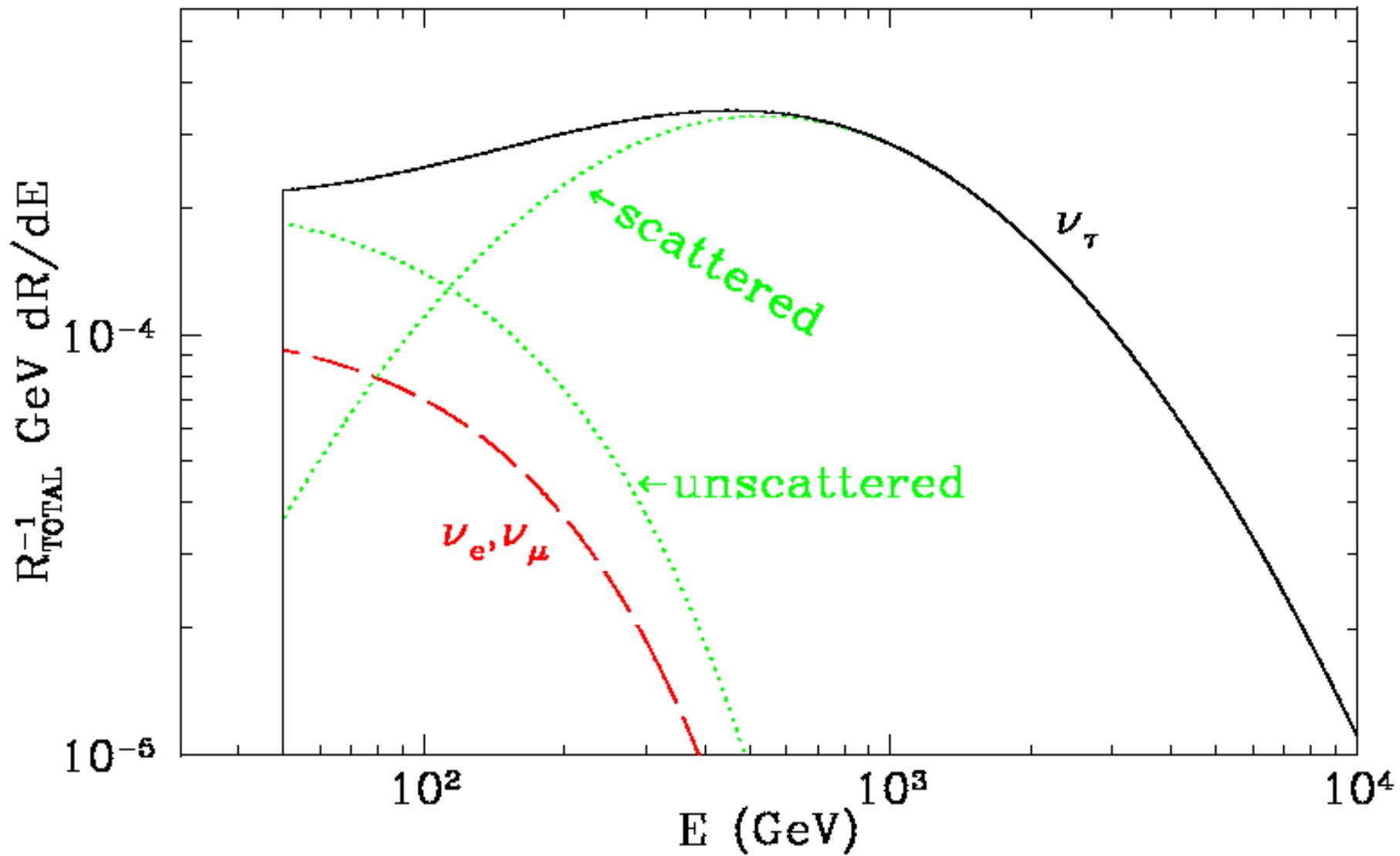
Emergent spectrum



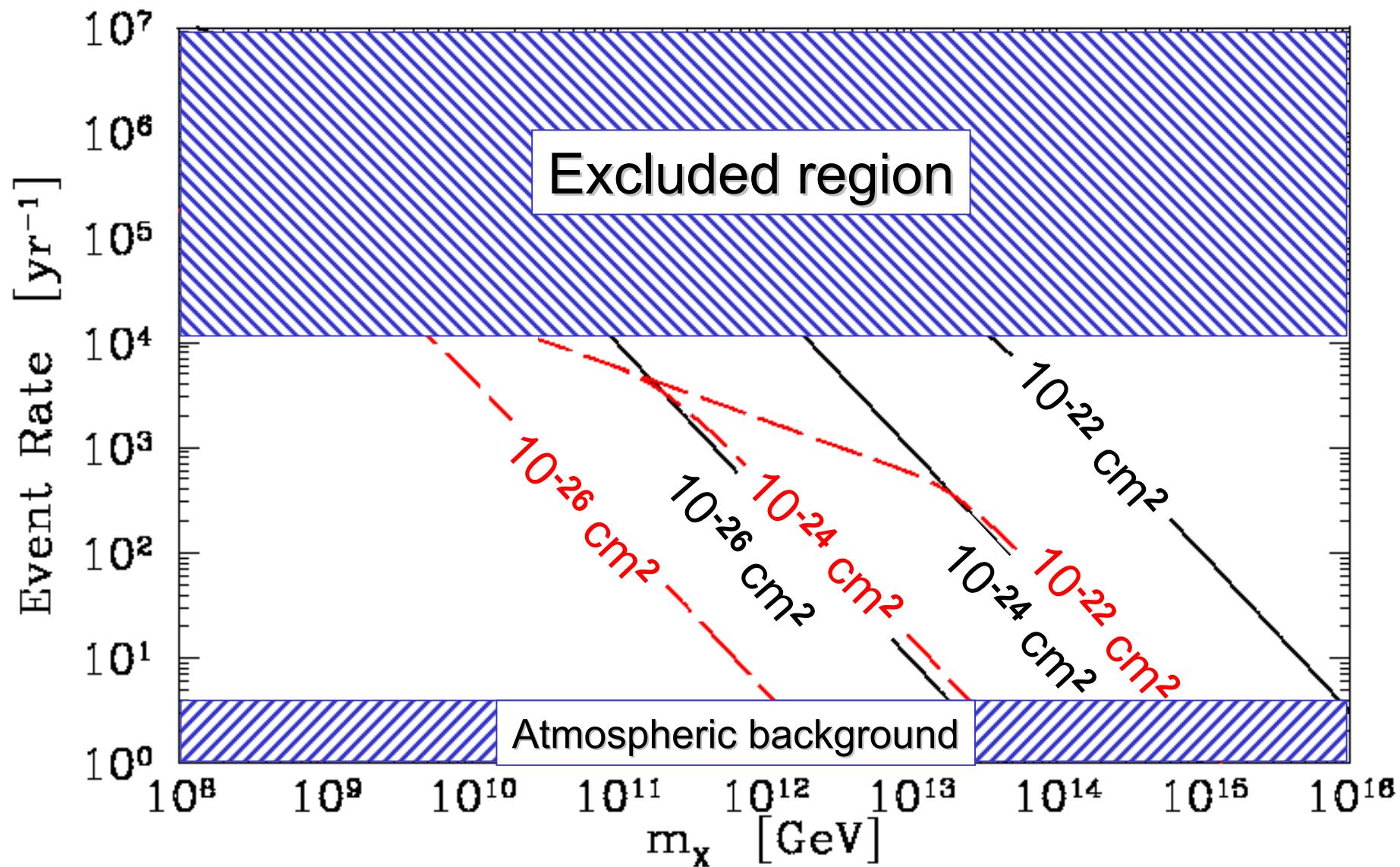
km³ **underice/ undersea neutrino telescopes**



Spectrum of detected events



Event rate



Nonbaryonic dark matter

Familiar candidate: thermal relic, i.e., a neutralino

“a simple, elegant, compelling explanation for a complex physical phenomenon”

“For every complex natural phenomenon there is a simple, elegant, compelling, wrong explanation.”

- *Tommy Gold*

Dark matter may be produced in inflation (the alarming phenomenon), be superheavy, and be sterile (or it may interact).

Dark Matter

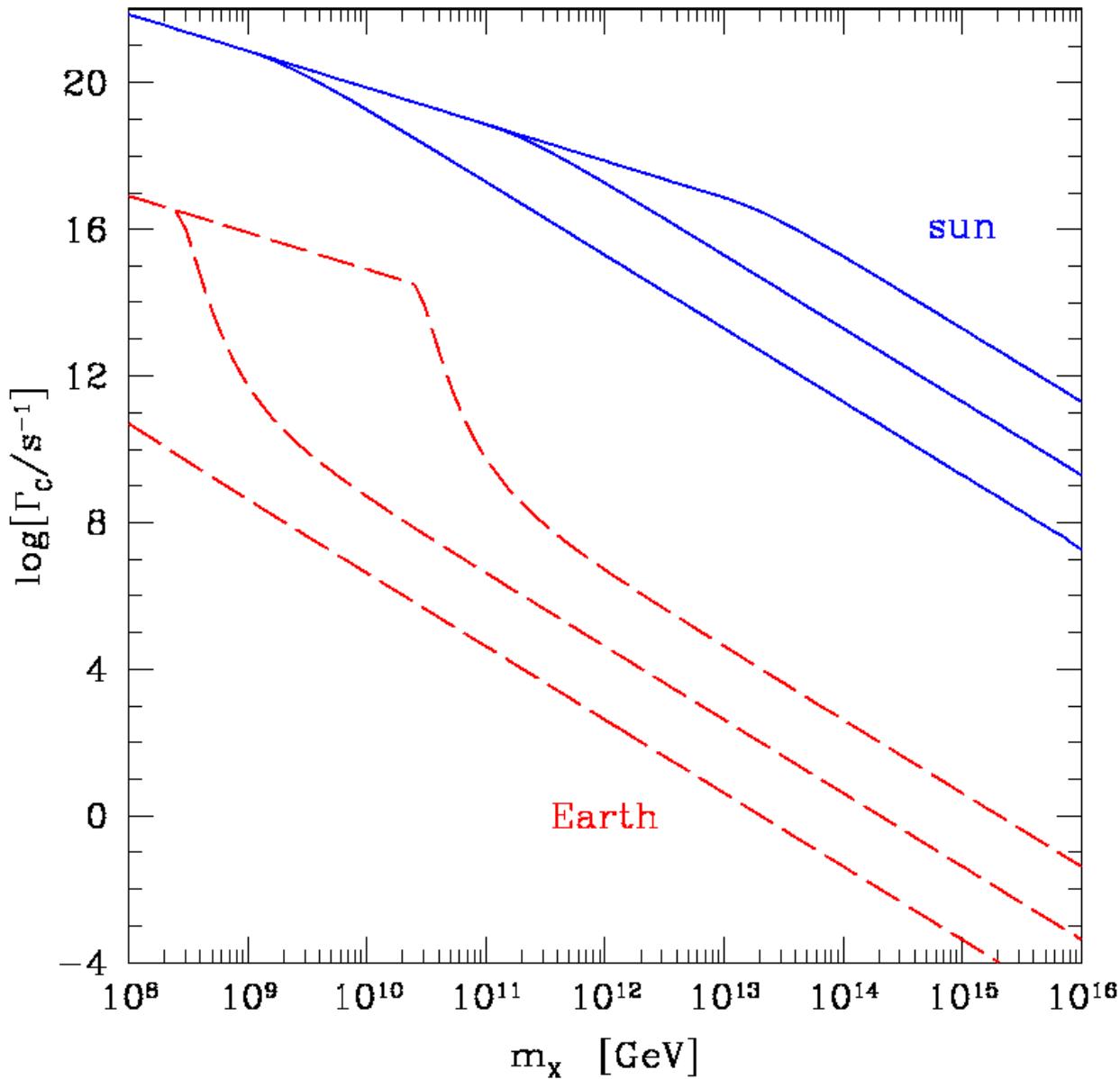
WIMP

or

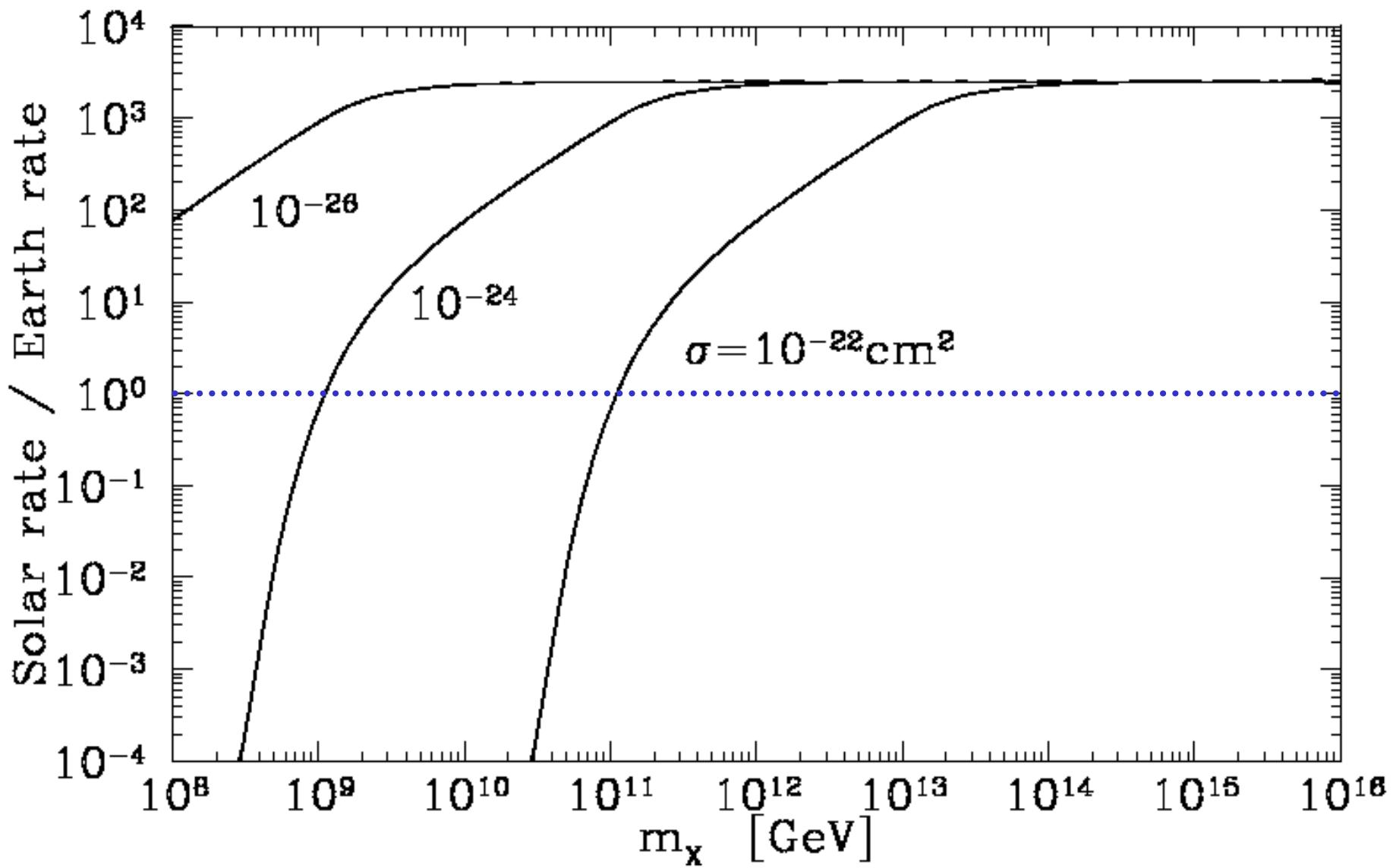
WIMPZILLA



Earth capture rate



Sun / Earth



Excluded region

